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Effect of Corrosion Inhibitors on Lubricity as Measured by the Ball-on-Cylinder Instrument

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This technical report has been reviewed and is approved for publication.

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This report is an investigation to determine the effects of corrosion inhibitors on the lubricity of different types of fuels. The lubricity level of each fuel sample was measured using the Interav Ball-on-Cylinder Tester. The three most common inhibitors currently used by the Air Force (herein referred to as Corrosion Inhibitors C1, C2 and C3) were tested in petroleum and shale JP-4, JP-8 and "isopar" with and without other additives present. "Normalization" procedures were used to evaluate inhibitor effectiveness relative to the wear scar of clay-treated fuels. Other additives were found to have effects on lubricity of fuel with corrosion inhibitor. Temperature variations of 13 degrees C had only a slight effect on fuel lubricity.

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FOREWORD

This technical report describes an experimental study of the effects of corrosion inhibitors on the lubricity of aviation turbine fuel. All of the work reported here was performed in-house under Work Unit 30480591, "Fuel Evaluation and Development" which is administered by the Fuels Branch (AFWAL/POSF), Fuels and Lubrication Division (POS), Air Force Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio. The authors wish to acknowledge the efforts of Mr. Timothy L. Dues who was instrumental in setting up the experiments being recorded here. All Ball-on-Cylinder measurements were performed by Mr. Miller and Mr. Flahive.

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LIST OF ABBREVIATIONS

AFB	Air Force Base
bbls	Barrels
BOC	Ball-on-Cylinder
C	Celcius
FSII	Fuel System Icing Inhibitor
Inc.	Incorporated
JP	Jet Propulsion
kbbl	thousand barrels
lbs	pounds
mm	millimeters
Norm.	Normalized
ppm	parts per million
psi	pounds per square inch
QPL	Qualified Products List
rpm	revolutions per minute
SLPM	Standard liters per minute
U.S.	United States
USAF	United States Air Force
%	percent
#	pounds

SECTION I

INTRODUCTION

As the world's supply of light crude oils continues to decrease, more and more refiners are using heavier feedstocks in order to produce distillate fuels. When the feedstocks were lighter, refiners needed little to no hydroprocessing technology (hydrotreating and hydrocracking) to produce their product slates. With current heavier crudes, high levels of sulfur, nitrogen, oxygen and other heteroatoms must be removed to meet the specifications of certain distillate fuels. Mono- and poly-aromatics rings must be saturated with hydrogen to produce a lighter, more usable fuel. These naturally occurring components of a fuel (sulfur, nitrogen, oxygen and aromatics) are precisely what imparts good lubricity to a fuel, according to many sources (References 1,2,12). Because of the lack of these natural lubricants in hydroprocessed fuels, the lubricity of hydrotreated distillate products has become a recurring problem.

The U.S. Air Force has certainly been one of the users who has experienced lubricity problems (References 3,4). In 1965, lubricity problems were discovered in aircraft with J57, J69 and J79 engines. Parts of the fuel systems for these engines had no lubricant except for the fuel itself; fuel pumps and fuel controls showed signs of wear due to metal to metal contact. It was quickly discovered that small amounts of corrosion inhibitor would impart acceptable lubricity to jet fuel. Corrosion inhibitors, by their very nature, tend to plate out on metal surfaces to prevent oxidation from occurring. The inhibitor also forms an interface which tends to keep two metal surfaces apart, thereby reducing wear caused by the contact of the metal surfaces. Thus, corrosion inhibitors seemed to be a natural "fix" to the lubricity problem which the fuel community was facing.

The Air Force approves all additives to be used in aviation turbine fuel and corrosion inhibitor use is outlined in a Qualified Products List (QPL) (Reference 5). The QPL prescribes the maximum allowable concentration and the minimum effective concentration for each of the corrosion inhibitors approved for use. Unfortunately, there is currently no straight-forward analytical method for measuring the type and amount of corrosion inhibitor present in a fuel. There is also no specification for fuel lubricity. The Air Force must rely on each fuel supplier to insure that if a fuel is hydroprocessed severely, it will be blended with corrosion inhibitor to produce an acceptable lubricity level.

A physical test was devised to test the lubricity of a jet fuel. The Furey Ball-on-Cylinder (BOC) Tester was used to determine the relative difference between a "good" lubricity fuel and a "poor" lubricity fuel. Subsequent improvements in this device resulted in a Ball-on-Cylinder Tester manufactured by Interav Corporation for the U.S. Air Force. This instrument proved to be a reliable and efficient method for measuring a fuel's lubricity.

In 1984, the Air Force was involved in the development of fuel from oil shale (Reference 6). Since raw shale oil contains large amounts of sulfur, nitrogen, oxygen, metals and aromatics, shale fuel had to be severely hydroprocessed to produce JP-4 jet fuel. The JP-4 produced from this program was to be used in full scale engine tests and flight tests with the TF30 and F-111 aircraft. Knowing that the shale fuel would have poor lubricity, the Air Force blended all its fuels with corrosion inhibitor. After transferring fuel from tanks to trucks to pipelines, etc., the corrosion inhibitor decreased in effectiveness due to "plating out" of the additive on metal surfaces. Thus, when engine tests were conducted, fuel pump wear occurred due to poor lubricity fuel (Reference 7).

This incident indicated the need for the Air Force to closely monitor lubricity levels for hydroprocessed shale fuel. Future engine tests (TF30 Accelerated Mission Test) were conducted while performing Ball-on-Cylinder runs of each batch of fuel and blending in corrosion inhibitor as needed (Reference 8). No batch of fuel was used in the engine if the lubricity was poor. By controlling the lubricity level with corrosion inhibitor additions, this engine showed no signs of fuel pump wear, even though severely hydrotreated shale fuel was used.

The effectiveness of corrosion inhibitors has been the subject of several investigations by the Air Force and others (Reference 4). Because of the improved accuracy of the new BOC instrument, investigations of the effects of corrosion inhibitors on fuel lubricity were repeated in this study. The ultimate objective of the testing was to determine which of the most frequently used Air Force-approved corrosion inhibitors is most effective in improving fuel lubricity. Information sought included additive levels sufficient for acceptable fluid lubricity, effect of increasing additive concentration on fuel lubricity, and synergistic effects of other fuel additives on the ability of the corrosion inhibitors to improve fuel lubricity.

SECTION II

EXPERIMENTAL

A. Test Plan

The Qualified Products List (QPL) for corrosion inhibitors lists some 13 different additives approved for use in aviation fuel. Of these 13, three account for about 80% of the JP-4 fuel treated with corrosion inhibitor. In order to simplify the testing matrix, only the three most common corrosion inhibitors were evaluated. These are referred to herein as Corrosion Inhibitor C2, Corrosion Inhibitor C1 and Corrosion Inhibitor C3. There were three parts to this study. Part I was an investigation of the effects of different concentrations of the three corrosion inhibitors on the lubricity of four fuels. Part II involved testing the change in fuel lubricity over a 6-month period for various fuels and additives. Part III considered the effect of other additives on the lubricity of fuel with corrosion inhibitor.

1. Fuels

The following fuels were evaluated in part I of this study:

a. Clay Treated Shale JP-4

b. Clay Treated Petroleum JP-4

c. Clay Treated Petroleum JP-8

d. Isopar - an Isoparaffinic Solvent

Clay treating was necessary to insure that the fuel had no additives prior to testing. This process removes most polar compounds leaving only hydrocarbons with no additives (References 9,13).

2. Concentrations of Additives

Five different concentrations of each of the three corrosion inhibitors were used in Part I. Concentration is usually measured in pounds of additive per thousand barrels of jet fuel (1 barrel = 42 gallons) or lbs/1000 bbls. The five concentrations used were:

a. 0 lbs / 1000 bbls	
b. 2 lbs / 1000 bbls	minimum effective concentration
c. 3 lbs / 1000 bbls	
d. 6 lbs / 1000 bbls	
e. 8 lbs / 1000 bbls	maximum allowable concentration

All combinations of fuels, corrosion inhibitors and concentrations of corrosion inhibitor were run on the Ball-on-Cylinder (BOC) instrument at 25 degrees C and 38 degrees C. Cylinders used in the experiment were "qualified" by first running a standard mixture and determining a wear scar diameter. If the wear scar from the qualification run was within 0.45 +/- 0.02 mm, the cylinder was approved for use. All actual fuel measurements were done in duplicate; further runs were necessary if duplicate runs did not have acceptable repeatability.

In Part II, 0-month, 3-month and 6-month measurements were made to evaluate the effect of time on corrosion inhibitor effectiveness. All measurements were made in duplicate at two different temperatures for two concentrations of each inhibitor in specific fuels.

Part III of the program involved synergistic effects of other additives with corrosion inhibitors. Corrosion Inhibitor C2, Corrosion Inhibitor C1 and Corrosion Inhibitor C3 were used at minimum effective concentration and maximum allowable concentration (3 lbs/1000 bbls and 8 lbs/1000 bbls). The test fuels used were petroleum JP-4 and petroleum JP-8 . STADIS 450 (anti-static additive) and FSII (Fuel System Icing Inhibitor) were used in all blends with two antioxidants, herein referred to as Antioxidant A1 and Antioxidant A2. Again, test temperatures or 25 and 38 degrees C were used and all samples were run in duplicate.

B. BOC Operation

Diagrams of the BOC instrument are shown in Figures 1,2 and 3 (Reference 10). The following is a summary of the operating conditions and procedure: (Reference 11)

1. Summary of Standard Operating Conditions

a. Ball Load	1000 grams
b. Cylinder Rotational Speed	240 rpm +/- 2
c. Test Duration	30 minutes
d. Fuel Volume	50 ml +/- 0.5
e. Test Fluid Temperature	25 C +/- 1 and 38 C +/- 1
f. Compressed Air Supply	less than 50 ppm water less than 0.1% hydrocarbons
g. Conditioned Air (To Reservior)	10% relative humidity +/-0.2
(1) Conditioned purge air flow over fuel during test	3.8 SLPM (30 minutes)
(2) Conditioned fuel aeration flow through fuel in reservior	0.5 SLPM (15 minutes)

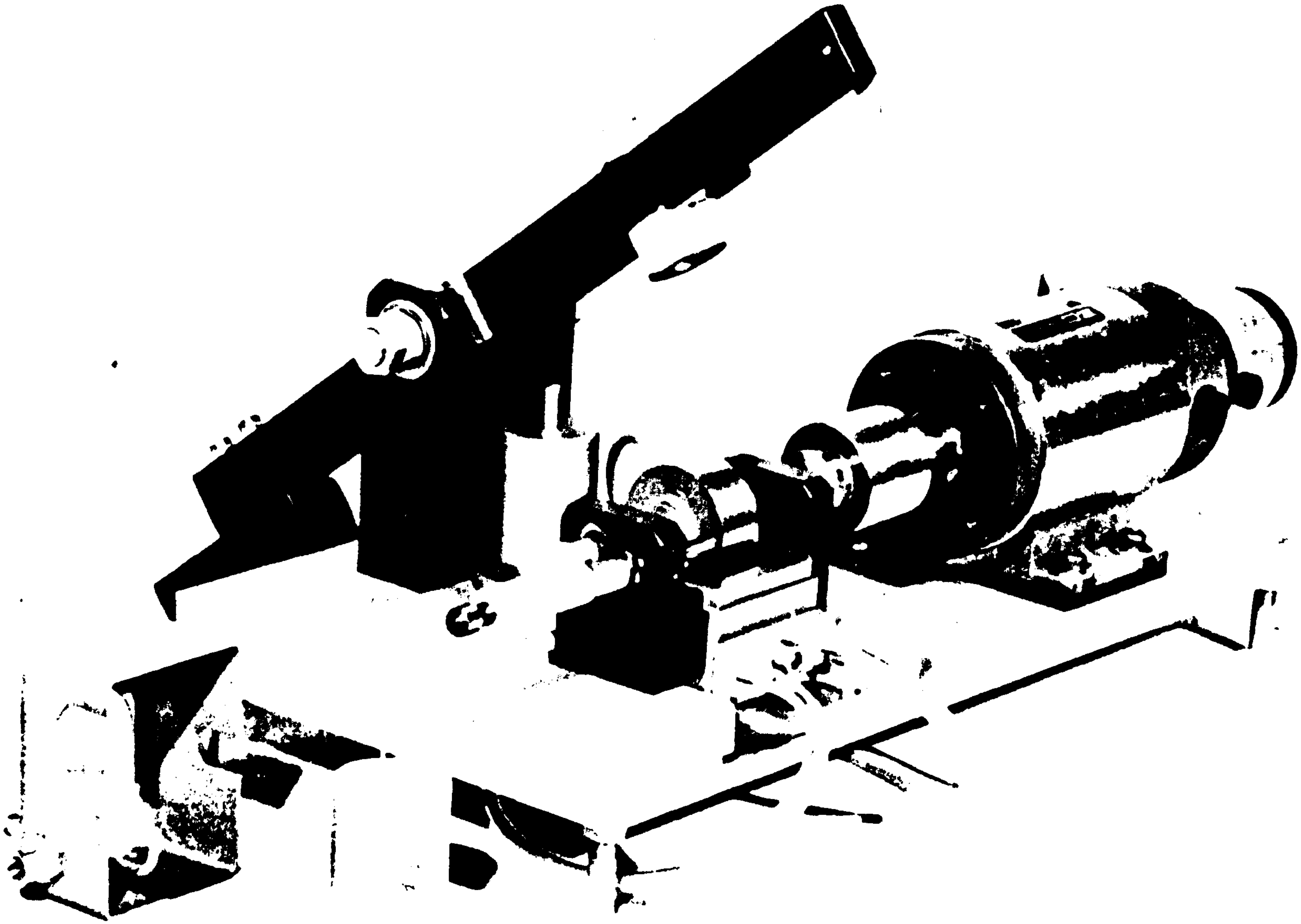

Figure 1. The Ball-on-Cylinder Lubricity Tester

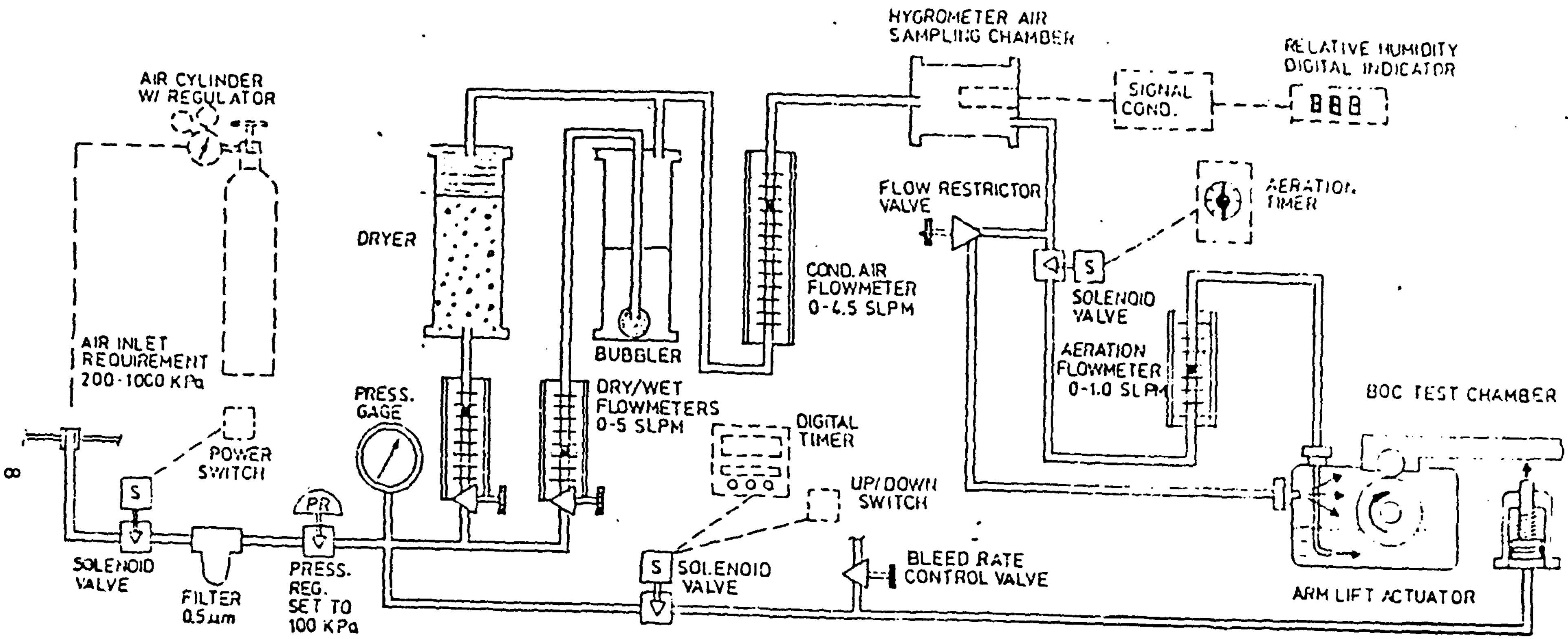

Figure 2. Ball-on-Cylinder Flow Schematic

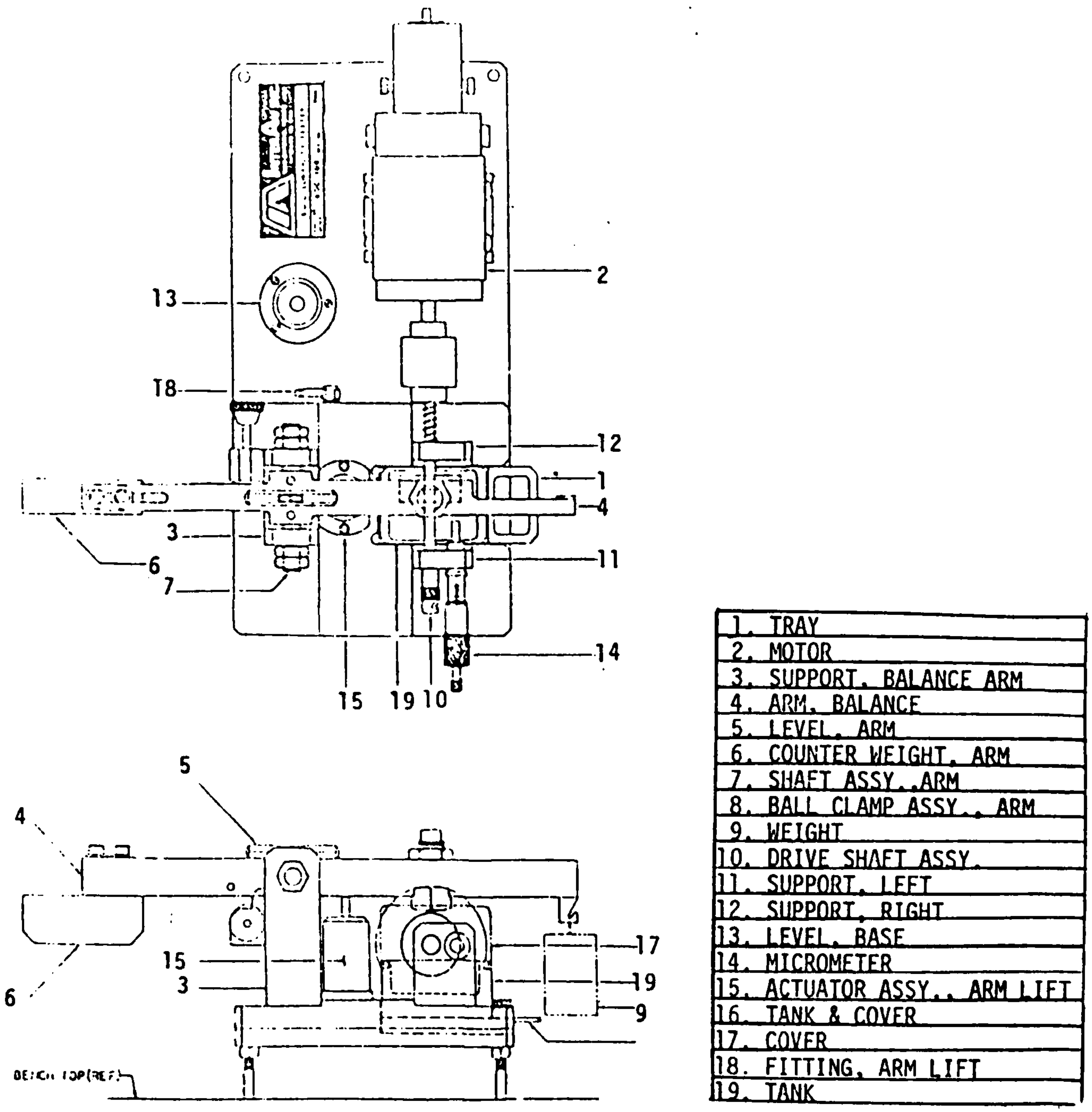

Figure 3. Ball-on-Cylinder Assembly Schematic

2. Identification of Test Cylinders and Balls

a. Test cylinders are to be numbered consecutively when received new. A one-eighth inch letter and number hand stamp can be used to permanently stamp identification markings of the set screw hub size on the cylinder. A letter and number system can be used to identify batches and lots of cylinders. The U.S. Air Force uses a letter code followed by consecutive numbers.

b. Test balls are to be numbered and recorded on the test data sheet along with the cylinder wear track number for future reference. USAF numbering uses the following system: BOC-100-Serial Number of BOC Instrument-Consecutive Ball number (i.e., BOC-100-019-0700). Completed test balls can be stored in 4" x 4" plastic interlocking bags.

3. Test Procedures

a. Move power switch to "on" position. Arm lift pneumatic actuator switch should be in the "up" position.

b. Turn on compressed air cylinder. Adjust delivery pressure on second stage of regulator to 25 psi.

c. Adjust, if necessary, console air pressure to approximately 100 KPa (14.5 psi)

d. Using flow meters controlling the wet and dry air flows, adjust conditioned air flow to read 3.8 standard liters per minute (SLPM) while maintaining a 10% +/-0.2 reading on the percent relative humidity readout.

e. Note and record on the data sheet the position of the test cylinder by use of the micrometer. Spacing between the wear tracks on the cylinder should be 0.75mm. The first and last wear tracks on a cylinder should be approximately 1-2mm in from either side. If needed, install a pre-cleaned new or reground test cylinder and note the cylinder code on the data sheet. Assure that the micrometer probe is backed away from the cylinder.

f. Install a pre-cleaned reservoir by lifting reservoir and sliding blue elevating spacing platform under reservoir. Place thermocouple in the hole near the rear left side of the reservoir.

g. Install a pre-cleaned test ball by placing ball in a blue retaining ring. Place ball and ring in retaining nut, ball side down. Screw retaining nut onto the load arm and hand tighten. Gently wipe bottom of the ball with an iso-octane wetted kimwipe and wipe dry.

h. Using a pipette bulb, pipette 50 ml of the test fluid into reservoir. Place reservoir cover onto the reservoir. Attach 1/8" and 1/4" air lines to reservoir cover.

i. Lower load arm by pulling blue pull pin and hang test weight on end of arm. Test load is standard and it equals 1000 grams.

j. Start rotation of shaft and cylinder by switching motor drive to "on". Set or readjust rpm to 240 +/- 1.

k. Set fuel aeration timer for 15 minutes. Check fuel aeration flowmeter and adjust to 0.5 SLPM if necessary.

l. At completion of aeration, the whistle will sound. Move arm lift actuation switch to "down" position. In 10-15 seconds, the load arm will lower and the ball will gently make contact with the cylinder. Switch timer to the "on" position. Check all test condition readouts and adjust as necessary. Record all necessary information on data sheets.

m. At the end of 30 minutes, the whistle will sound and the test load arm will automatically spring up. Turn timer "off" and move arm lift actuator switch from "down" to "up."

n. Manually remove test weight. Lift test load arm up and secure with blue pull pin. Move motor drive switch to "off."

o. Remove test ball from retaining nut. Leave ball in the blue retaining ring and rinse with iso-octane to remove fuel. Wipe the ball clean with a kimwipe. Circle the wear scar with a permanent marking pen. The ball may now be removed from the retaining ring if desired.

p. Remove the reservoir cover and reservoir. Dispose of fuel and clean both as required.

q. Clean cylinder in the ultrasonic cleaner.

r. Measure the wear scar diameter with the microscope using the "best elipse" method.

4. <u>Periodic BOC Test with Reference Fluids</u>

a. Each time a new test cylinder is installed and started, a rerun should be made with the selected reference fuel to make certain that the new cylinder gives the same results as the previous cylinders within 0.02 mm. The current reference fuel is "Isopar," an isoparaffinic solvent with 8 lbs/1000 bbls of Corrosion Inhibitor C2 Corrosion Inhibitor/Lubricity Improver.

b. To initially determine the wear scar diameter value of the reference fuel, perform BOC lubricity measurements four times and average the results.

c. Each time a new cylinder is installed, perform a lubricity measurement using the reference fuel. This value should be +/- 0.02 mm from the standard wear scar diameter (WSD) value of the reference fuel. If the WSD difference is greater than 0.02 mm, repeat the test with another cylinder.

C. Blend Preparation

All base fuels were clay-treated according to ASTM D2550, Appendix C (Reference 13), in order to remove polar compounds and additives. The blends were prepared by weighing out additives and diluting them volumetrically to produce a concentrated stock solution. Since corrosion inhibitors generally have a shelf life of one year, care was taken to insure that fresh samples of additives were used. Blends made from the stock solutions were produced volumetrically using pipettes and volumetric flasks. All solutions were stored in amber glass bottles and stored at room temperature until testing was completed.

SECTION III

RESULTS

The results obtained for the experiments outlined above are summarized in Tables 1, 2 and 3. Table 1 shows wear scar diameter values representing the effect of concentration of corrosion inhibitors on fuel lubricity for four different fuels. Note that the wear scars given in this table are averages of duplicate runs. Table 2 is a summary of the six month testing program to determine whether the wear scars were changing significantly over time. Table 3 gives the results for fuels with additive packages, rather than just corrosion inhibitor. All of this raw wear scar diameter data will be examined and plotted in greater detail in Section IV, Discussion.

TABLE 1

SUMMARY OF WEAR SCAR RESULTS

CONC (#/kbbl)	PETROLEUM JP-4 Actual (mm)	PETROLEUM JP-4 Norm.	ISOPAR Actual (mm)	ISOPAR Norm.	SHALE JP-4 Actual (mm)	SHALE JP-4 Norm.	PETROLEUM JP-8 Actual (mm)	PETROLEUM JP-8 Norm.
Corrosion Inhibitor C2 at 25 degrees C								
0	.525	1	.843	1	.765	1	.68	1
2	.39	.743	.686	.814	.43	.562	.68	1
3	.37	.705	.585	.694	.373	.488	.548	.806
6	.35	.667	.535	.635	.42	.549	.455	.669
8	.332	.632	.489	.58	.39	.51	.443	.651
Corrosion Inhibitor C2 at 38 degrees C								
0	.543	1	.92	1	.84	1	.83	1
2	.393	.724	-	-	.47	.56	.83	1
3	.395	.727	-	-	.458	.545	.545	.657
6	.33	.608	-	-	.44	.524	.503	.606
8	.355	.654	-	-	.43	.512	.483	.582
Corrosion Inhibitor C3 at 25 degrees C								
0	.525	1	.843	1	.765	1	.68	1
2	.478	.91	.77	.913	.585	.765	.665	.978
3	.448	.853	.77	.913	.558	.729	.66	.971
6	.43	.819	.688	.816	.523	.684	.475	.699
8	.428	.815	.578	.686	.488	.638	.465	.684
Corrosion Inhibitor C3 at 38 degrees C								
0	.54	1	.92	1	.84	1	.83	1
2	.508	.941	.84	.913	.668	.795	.825	.994
3	.473	.876	.668	.726	.663	.789	.625	.753
6	.462	.856	.668	.726	.595	.706	.583	.702
8	.45	.833	.633	.688	.495	.589	.525	.633

TABLE 1

SUMMARY OF WEAR SCAR RESULTS (CONCLUDED)

CONC (#/kbbl)	PETROLEUM JP-4 Actual (mm)	Norm.	ISOPAR Actual (mm)	Norm.	SHALE JP-4 Actual (mm)	Norm.	PETROLEUM JP-8 Actual (mm)	Norm.
Corrosion Inhibitor Cl at 25 degrees C								
0	.525	1	.843	1	.765	1	.68	1
2	.405	.771	.745	.884	.445	.582	.6	.882
3	.385	.733	.61	.724	.43	.562	.5	.735
6	.358	.682	.543	.644	.413	.54	.438	.644
8	.325	.619	.545	.647	.4	.523	.413	.607
Corrosion Inhibitor Cl at 38 degrees C								
0	.54	1	.92	1	.84	1	.83	1
2	.44	.815	.773	.84	.483	.575	.825	.994
3	.403	.746	.74	.804	.475	.565	.735	.886
6	.353	.654	.635	.69	.465	.554	.555	.669
8	.34	.63	.605	.658	.405	.482	.49	.59

TABLE 2

WEAR SCAR READINGS FROM 6 MONTH TESTING

FOR PETROLEUM JP-4

	**** 0 MONTHS ****		**** 3 MONTHS ****		**** 6 MONTHS ****	
	TEMPERATURE		TEMPERATURE		TEMPERATURE	
	25 deg C	38 deg C	25 deg C	38 deg C	25 deg C	38 deg C
Petroleum JP-4 with:						
3 lbs/1000 bbls of NALCO 5403	0.385	0.403	0.398	0.42	0.38	0.415
8 lbs/1000 bbls of NALCO 5403	0.325	0.34	0.36	0.37	0.343	0.33
3 lbs/1000 bbls of DCI-4A	0.37	0.395	0.40	0.393	0.358	0.378
8 lbs/1000 bbls of DCI-4A	0.332	0.355	0.387	0.343	0.325	0.325
3 lbs/1000 bbls of Apollo PRI-19	0.558	0.663	0.553	0.533	0.503	0.49
8 lbs/1000 bbls of Apollo PRI-19	0.488	0.495	0.475	0.528	0.433	0.580

TABLE 2
WEAR SCAR READINGS FOR 6-MONTH TESTING (concluded)
FOR PETROLEUM JP-8

	**** Ø MONTHS ****		**** 3 MONTHS ****		**** 6 MONTHS ****	
	TEMPERATURE		TEMPERATURE		TEMPERATURE	
	25 deg C	38 deg C	25 deg C	38 deg C	25 deg C	38 deg C
Petroleum JP-8 with:						
3 lbs/1000 bbls of NALCO 5403	0.508	0.735	0.550	0.545	0.555	0.440
8 lbs/1000 bbls of NALCO 5403	0.413	0.490	0.435	0.478	0.390	0.478
3 lbs/1000 bbls of DCI-4A	0.548	0.545	0.535	0.588	0.500	0.525
8 lbs/1000 bbls of DCI-4A	0.443	0.483	0.450	0.498	0.425	0.475
3 lbs/1000 bbls of Apollo PRI-19	0.660	0.625	0.698	0.623	0.760	0.615
8 lbs/1000 bbls of Apollo PRI-19	0.465	0.525	0.540	0.543	0.430	0.540

TABLE 3

SUMMARY OF THE EFFECTS OF OTHER ADDITIVES
ON WEAR SCAR DIAMETER

CORROSION INHIBITOR (lbs / 1000 bbls)	ANTIOXIDANT (lbs / 1000 bbls)	WSD (mm)
PETROLEUM JP-4		
25 degrees C		
C1 (3.0)	A1 (7.0)	.408
C1 (8.0)	A1 (7.0)	.36
C2 (3.0)	A1 (7.0)	.38
C2 (8.0)	A1 (7.0)	.353
C1 (3.0)	A2 (7.0)	.375
C1 (8.0)	A2 (7.0)	.363
C2 (3.0)	A2 (7.0)	.378
C2 (8.0)	A2 (7.0)	.378
C1 (3.0)	NO ANTIOXIDANT	.385
C1 (8.0)	NO ANTIOXIDANT	.325
C2 (3.0)	NO ANTIOXIDANT	.37
C2 (8.0)	NO ANTIOXIDANT	.332
38 degrees C		
C1 (3.0)	A1 (7.0)	.425
C1 (8.0)	A1 (7.0)	.37
C2 (3.0)	A1 (7.0)	.41
C2 (8.0)	A1 (7.0)	.363
C1 (3.0)	A2 (7.0)	.42
C1 (8.0)	A2 (7.0)	.378
C2 (3.0)	A2 (7.0)	.41
C2 (8.0)	A2 (7.0)	.363
C1 (3.0)	NO ANTIOXIDANT	.403
C1 (8.0)	NO ANTIOXIDANT	.34
C2 (3.0)	NO ANTIOXIDANT	.395
C2 (8.0)	NO ANTIOXIDANT	.355

TABLE 3

SUMMARY OF THE EFFECTS OF OTHER ADDITIVES ON WEAR SCAR DIAMETER (concluded)

CORROSION INHIBITOR (lbs / 1000 bbls)	ANTIOXIDANT (lbs / 1000 bbls)	WSD (mm)
PETROLEUM JP-8		
25 degrees C		
C1 (3.0)	A1 (7.0)	.455
C1 (8.0)	A1 (7.0)	.435
C2 (3.0)	A1 (7.0)	.415
C2 (8.0)	A1 (7.0)	.378
C1 (3.0)	A2 (7.0)	.508
C1 (8.0)	A2 (7.0)	.41
C2 (3.0)	A2 (7.0)	.443
C2 (8.0)	A2 (7.0)	.398
C1 (3.0)	NO ANTIOXIDANT	.5
C1 (8.0)	NO ANTIOXIDANT	.413
C2 (3.0)	NO ANTIOXIDANT	.548
C2 (8.0)	NO ANTIOXIDANT	.443
38 degrees C		
C1 (3.0)	A1 (7.0)	.49
C1 (8.0)	A1 (7.0)	.468
C2 (3.0)	A1 (7.0)	.46
C2 (8.0)	A1 (7.0)	.463
C1 (3.0)	A2 (7.0)	.493
C1 (8.0)	A2 (7.0)	.438
C2 (3.0)	A2 (7.0)	.485
C2 (8.0)	A2 (7.0)	.445
C1 (3.0)	NO ANTIOXIDANT	.735
C1 (8.0)	NO ANTIOXIDANT	.49
C2 (3.0)	NO ANTIOXIDANT	.545
C2 (8.0)	NO ANTIOXIDANT	.483

SECTION IV

DISCUSSION

A. Effects of Concentration of each Additive on Four Fuels

1. Base Fuels: Figure 4 is a representation of wear scar diameters for each fuel without any additives. The fuels were run at two different temperatures (25 and 38 degrees C). The figure shows that 38 C readings are generally higher than 25 C readings; this observation seemed to hold for the remainder of the study. This point will be discussed in further detail in the Recommendations Section. Figure 4 may also provide another clue to determining the causes of good or poor fuel lubricity; notice that the shale JP-4 wear scar diameter is much larger than the petroleum JP-4 scar. A possible explanation may be that the heteroatom concentration in shale-derived material is lower due to severe hydroprocessing. These natural lubricants are still present in petroleum JP-4, thereby imparting good lubricity.

Lubricity appears to be related to other fuel properties besides heteroatom concentration. Petroleum JP-8 has a fairly poor lubricity in spite of being a petroleum product. Therefore, it may be possible that boiling range or volatility has an effect on fuel lubricity. Isopar, being an isoparaffinic solvent, is understandably a poor lubricity fluid. It has none of the heteroatoms or aromatic molecules that most natural lubricants generally have. The data shown in Figure 4 seem to be consistent in terms of temperature - the higher temperature runs generally produced higher wear scars.

2. Effect of Corrosion Inhibitor Cl: Figures 5a and 5b represent the addition of Corrosion Inhibitor Cl to four different fluids. Corrosion

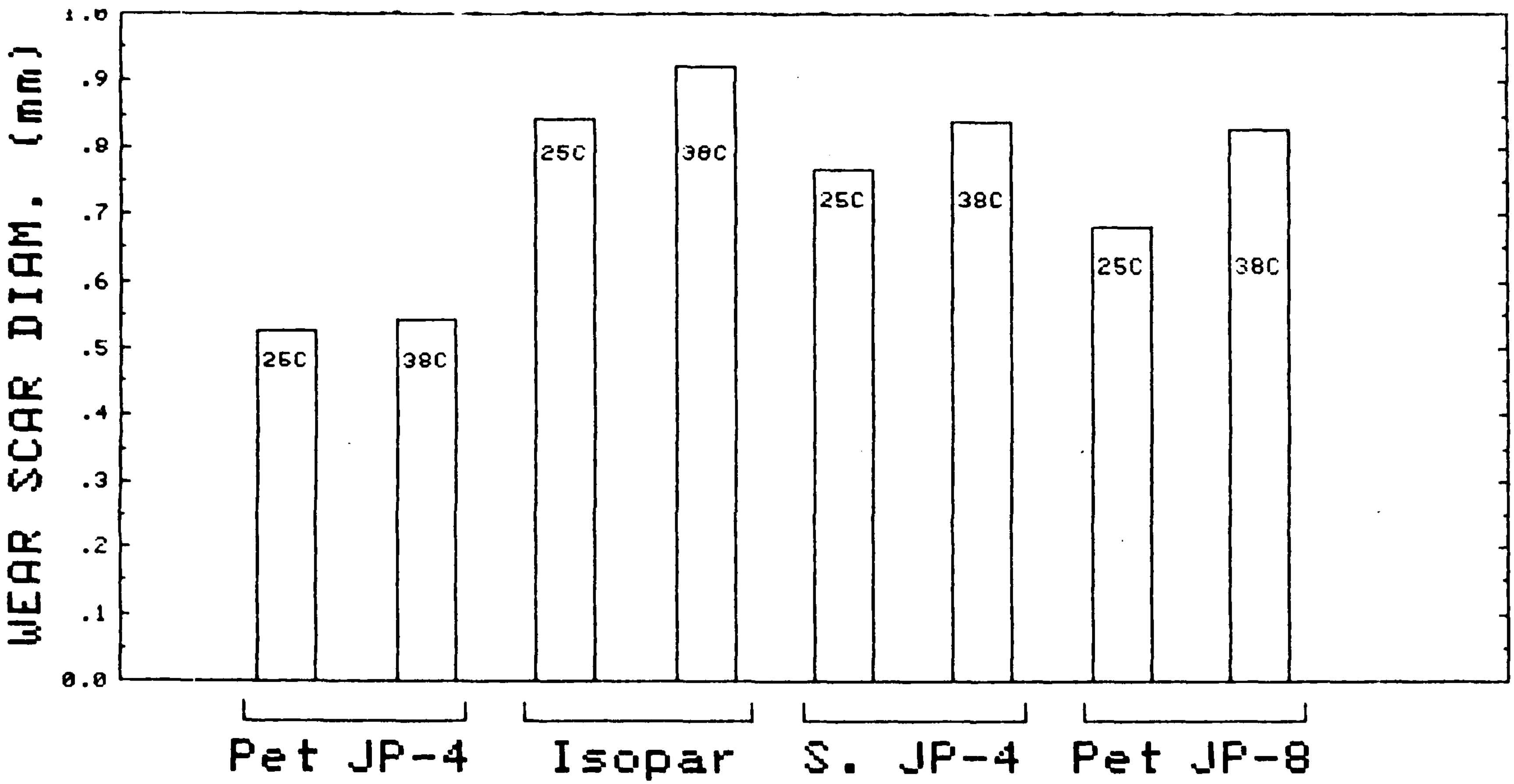

Figure 4. Wear Scar Diameter for Four Fuels with No Lubricity Improver

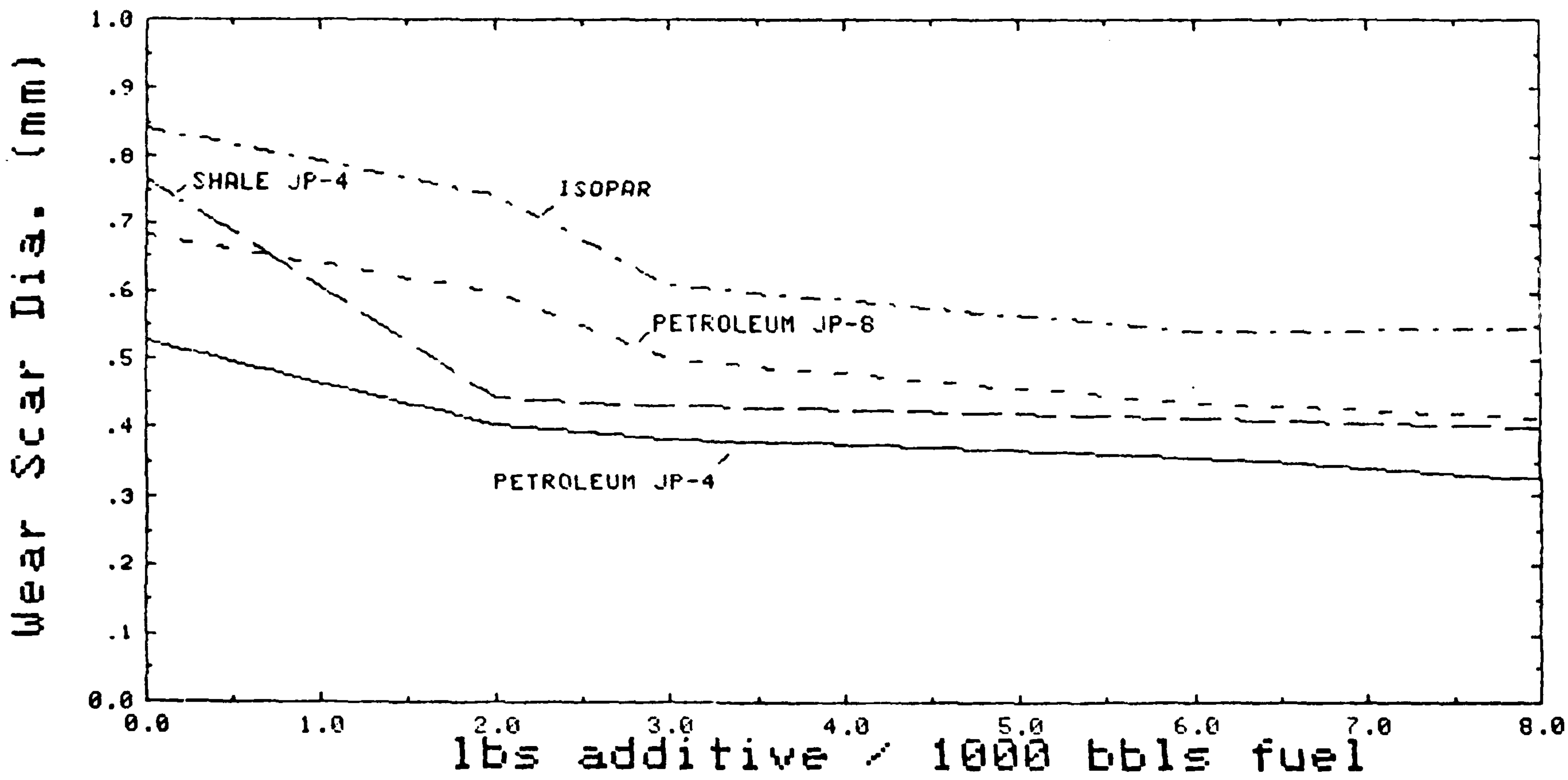

Figure 5a. Effect of Cl on Fuel Lubricity at 25 Degrees C

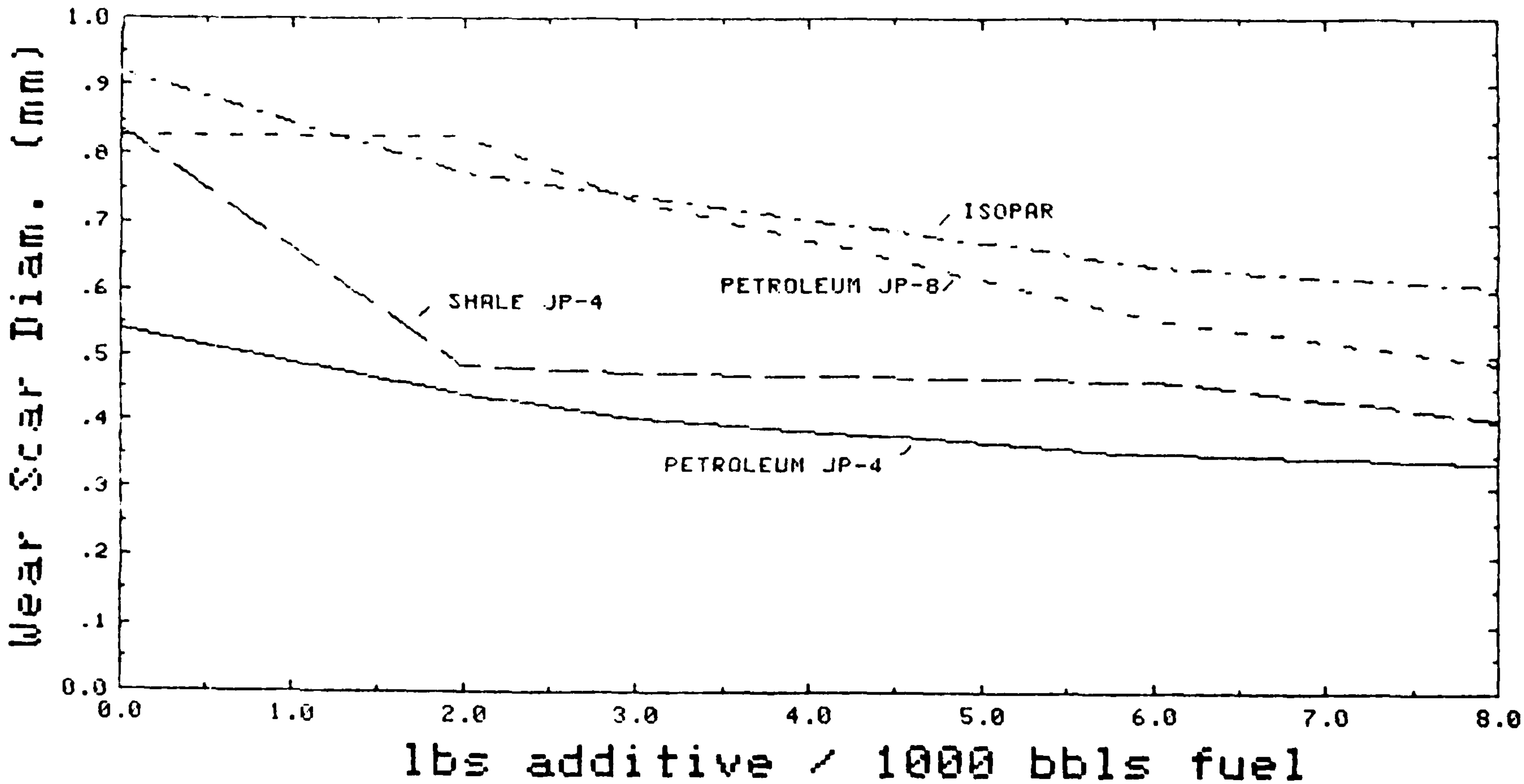

Figure 5b. Effect of CI on Fuel Lubricity at 38 Degrees C

Inhibitor C1 was the most often used corrosion inhibitor for Air Force use in fiscal year 1985, according to a recent survey (Reference 14). This figure aptly shows that Corrosion Inhibitor C1 will lower the wear scar diameter of each type of fuel. All of the fuels considered here had their lubricity "level out" with as little as 6 lbs/1000 bbls of additive. Thus, increasing corrosion inhibitor concentration beyond the maximum allowable concentration (8 lbs/1000 bbls) would not decrease wear scar diameter any further.

Shale JP-4 shows a very notable decrease in wear scar diameter for minimum amounts of corrosion inhibitor. Petroleum JP-8 with 2 lbs/1000 bbls of Corrosion Inhibitor C1 does not show much improvement at all in comparison to shale JP-4. Overall, it seemed that "minimum required" amount of Corrosion Inhibitor C1 has the greatest effect on fuel lubricity as measured by wear scar diameter. Petroleum JP-8, as an exception, seems to require more than the "minimum required" amount of corrosion inhibitor before its lubricity improves substantially.

3. Effect of Corrosion Inhibitor C2: The second most-used additive for 1985 seems to cause changes in lubricity very similar to Corrosion Inhibitor C1. In Figures 6a and 6b, "minimum required" amounts of additive decrease wear scar diameter substantially for both shale and petroleum JP-4. Isopar and petroleum JP-8 are less affected by minimal (2.0 lbs/1000 bbls) amounts of Corrosion Inhibitor C2. Notice that the wear scar trends are very similar at 25 degrees C and 38 degrees C.

4. Effect of Corrosion Inhibitor C3: The wear scars obtained using this additive were noticeably higher than those with the first two additives (See Figures 7a and 7b). Still, the same trends can be seen; any decrease in wear scar for JP-4 is obtained due to small amounts of additive. JP-8 requires more additive to lower fuel lubricity.

5. Normalized Wear Scar Data: Normalizing wear scar data was an

interesting and consistent way of comparing fuel lubricity data. Normalized wear scar represents the ability of an additive to lower wear scar relative to the wear scar of the fuel without additive. Thus, a normalized value might be obtained by dividing the wear scar diameter of a fuel with the wear scar diameter of the clay-treated fuel (no additive). One could then compare additives on their ability to decrease wear scar using a scale of 0 to 1. The normalization data are shown as Figures 8a and 8b, 9a and 9b, and Figures 10a and 10b.

B. Effect of Ambient Storage on Wear Scar Data

This part of the experiment attempted to show changes in wear scar diameter with ambient storage: specifically, how the corrosion inhibitors lose effectiveness over time? The answer to this question was not clear from this study. In Figures 11 and 12, it is not apparent that wear scar diameters are decreasing consistently. Occasionally, a fuel will have decreasing wear scar, but wear scar will also increase in as many cases. Thus there is not an observable change in wear scar diameter due to ambient storage in glass bottles.

C. Effect of Additive Packages: Synergistic Effects

The purpose of these experiments was to determine what trends in lubricity levels, if any, could be seen due to the addition of anti-static additive, anti-icing inhibitor, and either Antioxidant A1 or Antioxidant A2, using Corrosion Inhibitor C1 or Corrosion Inhibitor C2 as corrosion inhibitors. The experiment was conducted with both petroleum JP-4 and petroleum JP-8 . Although there were no obvious conclusions to be made, the following observations were noted:

1. Wear scar increased when either antioxidant was added to JP-4 with Corrosion Inhibitor C1 or Corrosion Inhibitor C2 in any concentration.

2. Wear scar decreased when either antioxidant was added to JP-8 with either Corrosion Inhibitor C1 or Corrosion Inhibitor C2. This decrease (in

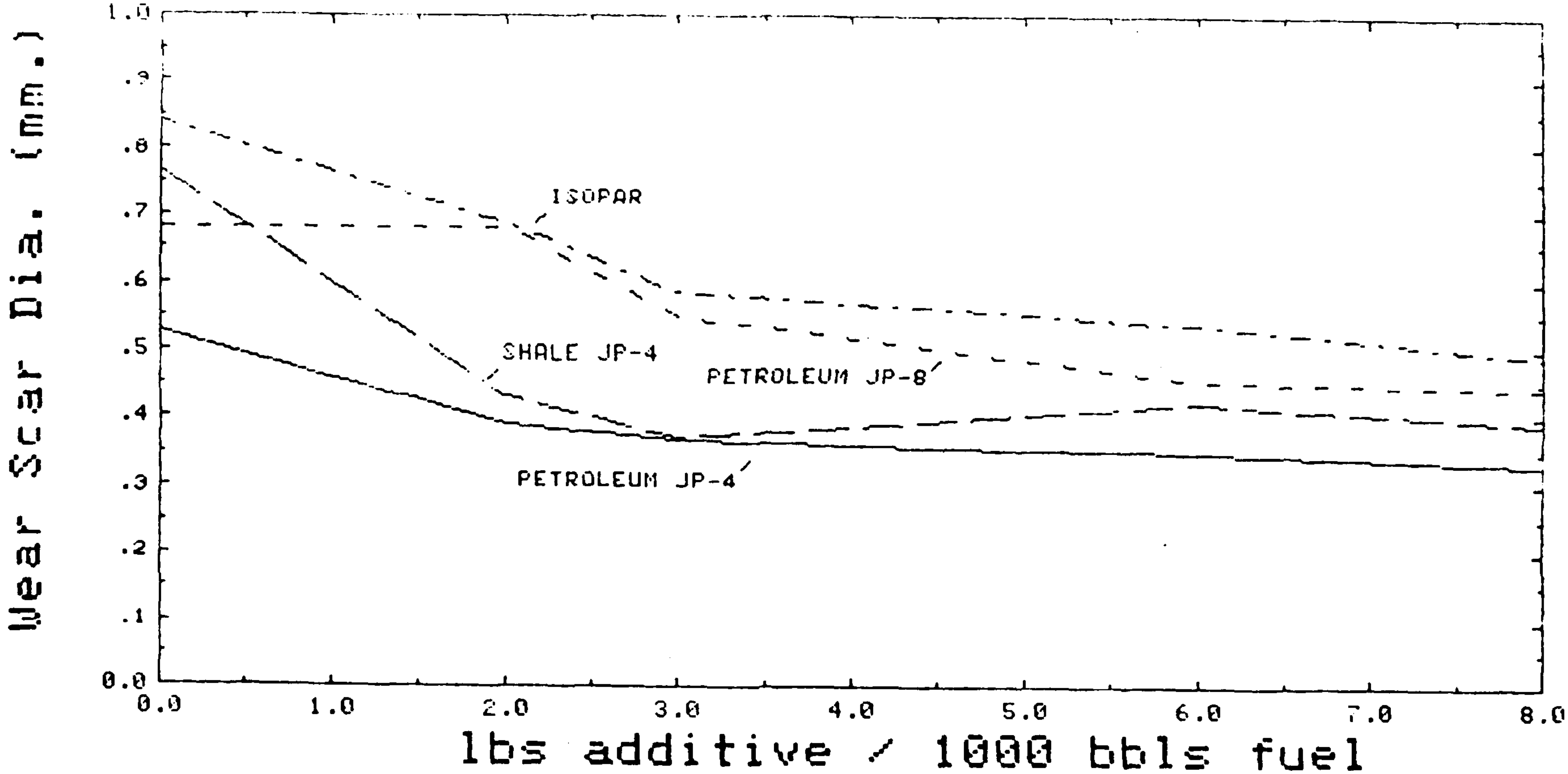

Figure 6a. Effect of C2 on Fuel Lubricity at 25 Degrees C

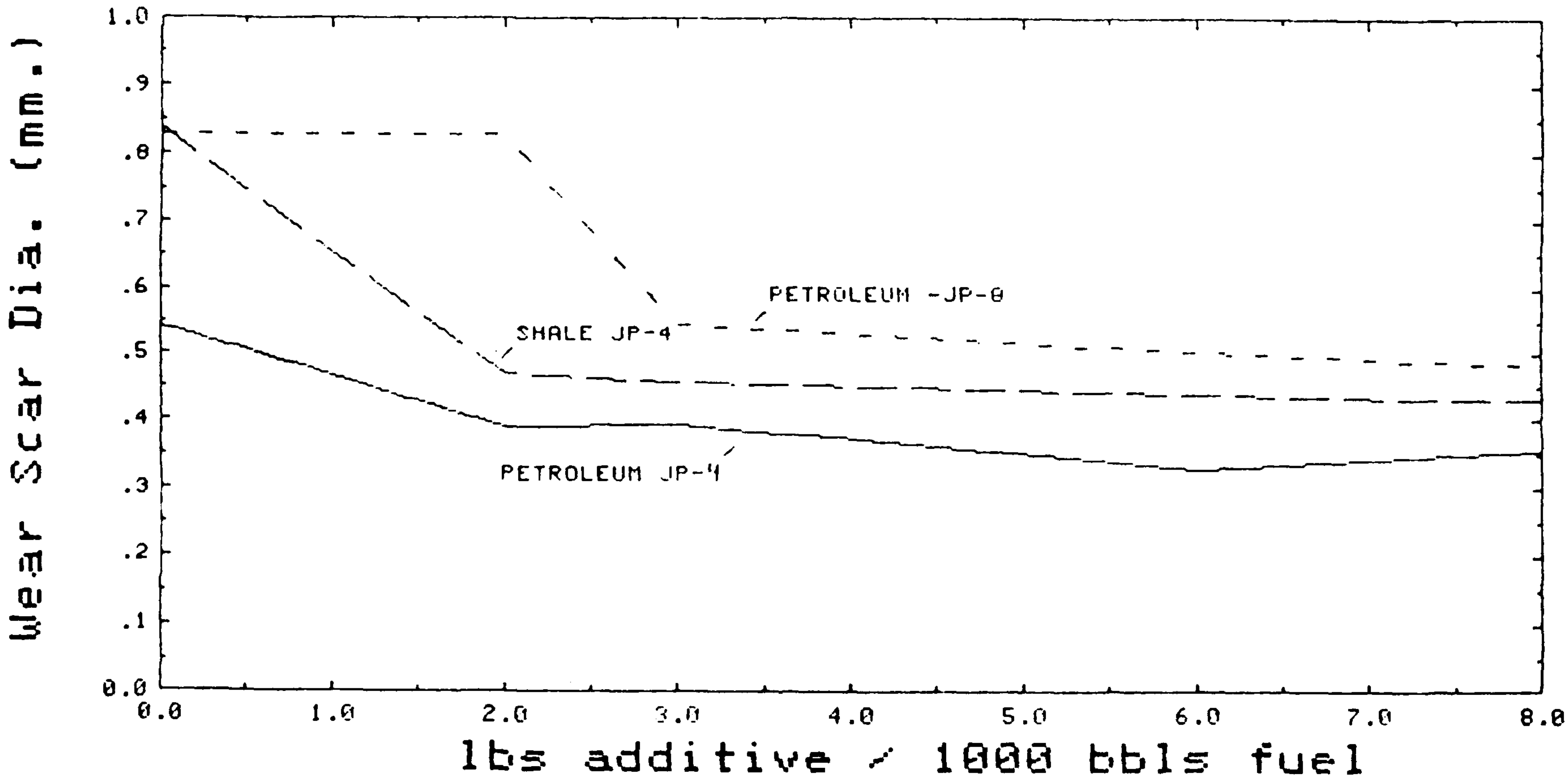

Figure 6b. Effect of C2 on Fuel Lubricity at 38 Degrees C

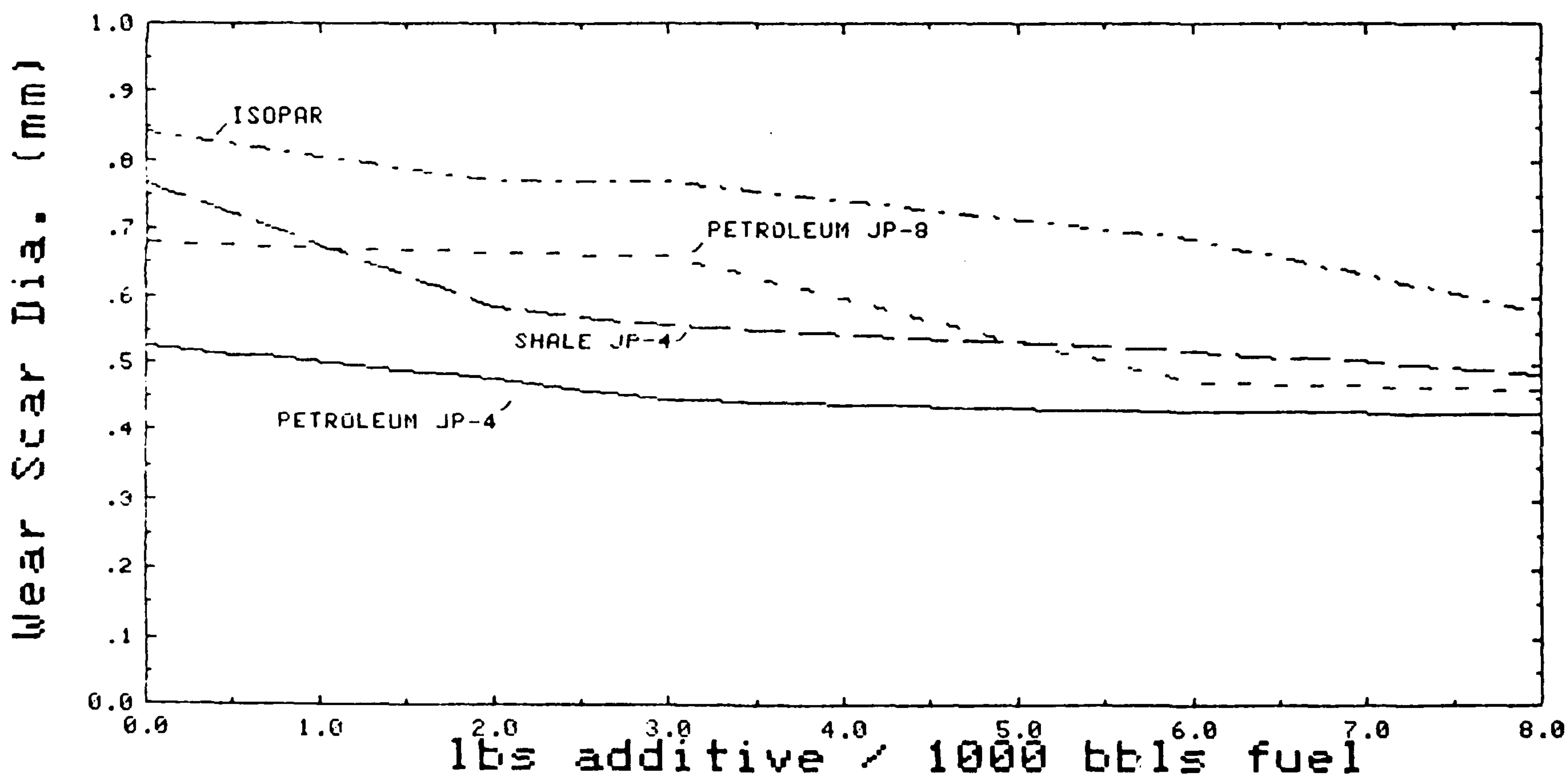

Figure 7a. Effect of C3 on Fuel Lubricity at 25 Degrees C

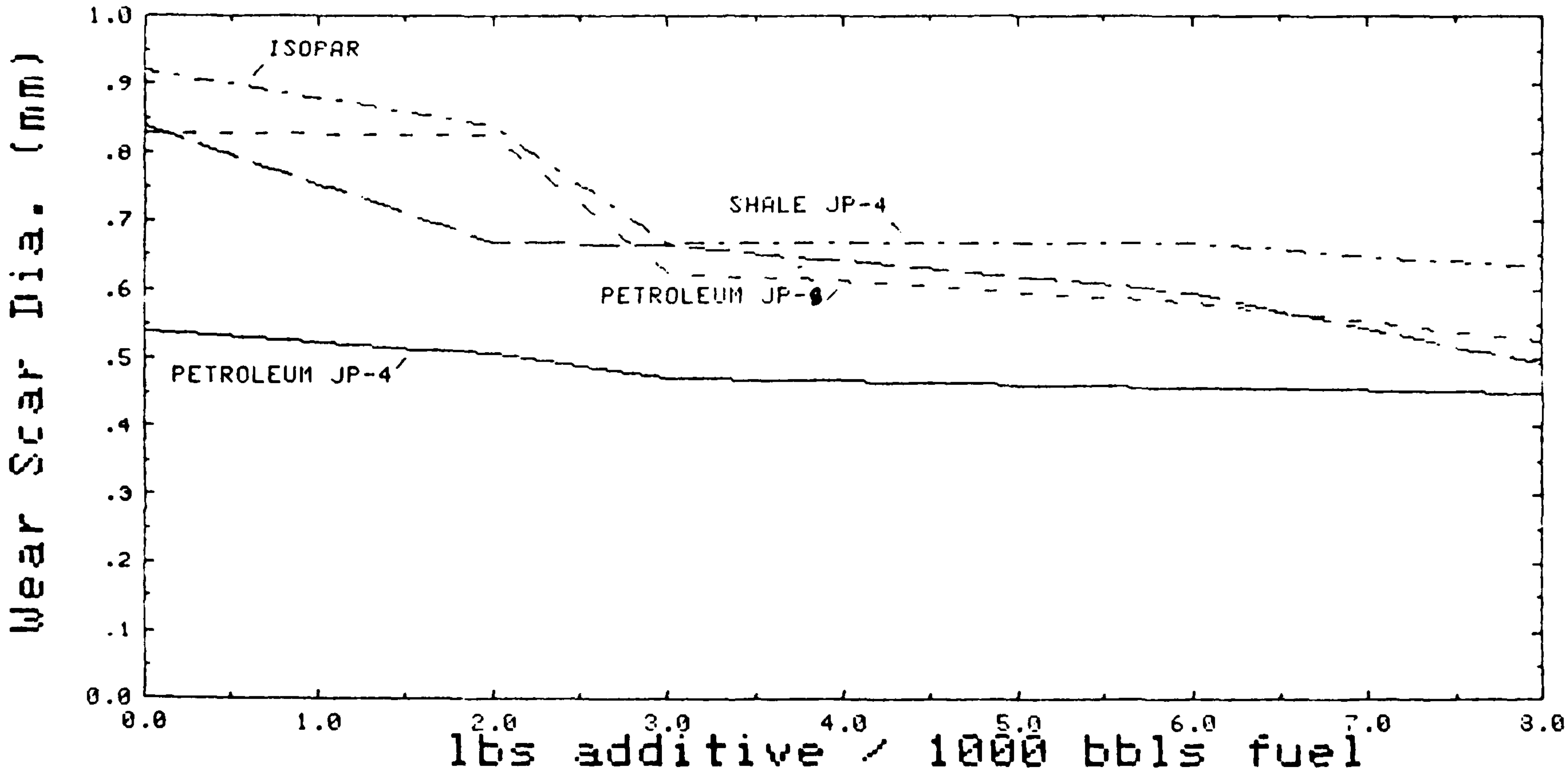

Figure 7b. Effect of C3 on Fuel Lubricity at 38 Degrees C

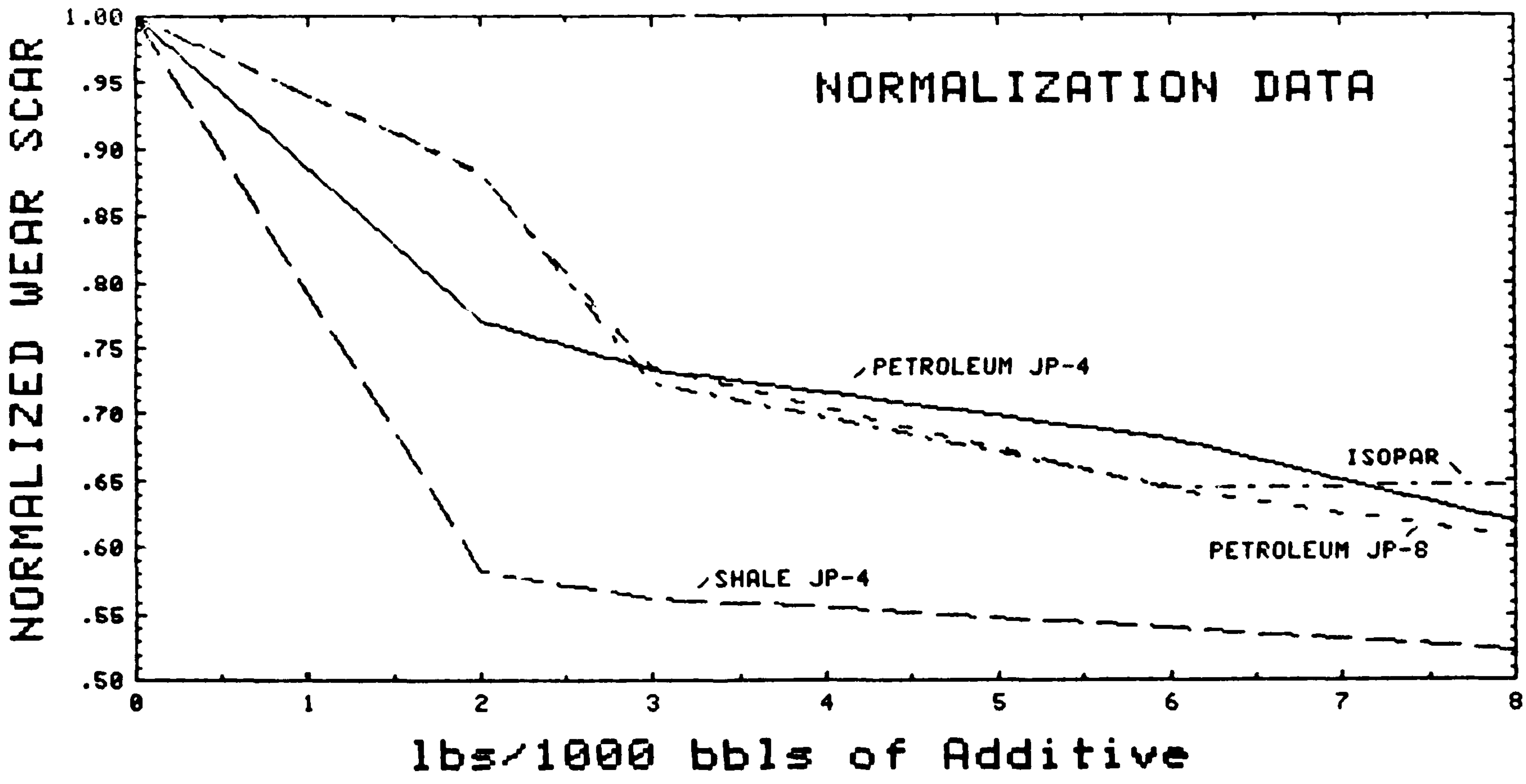

Figure 8a. Normalization Data: Cl at 25 Degrees C

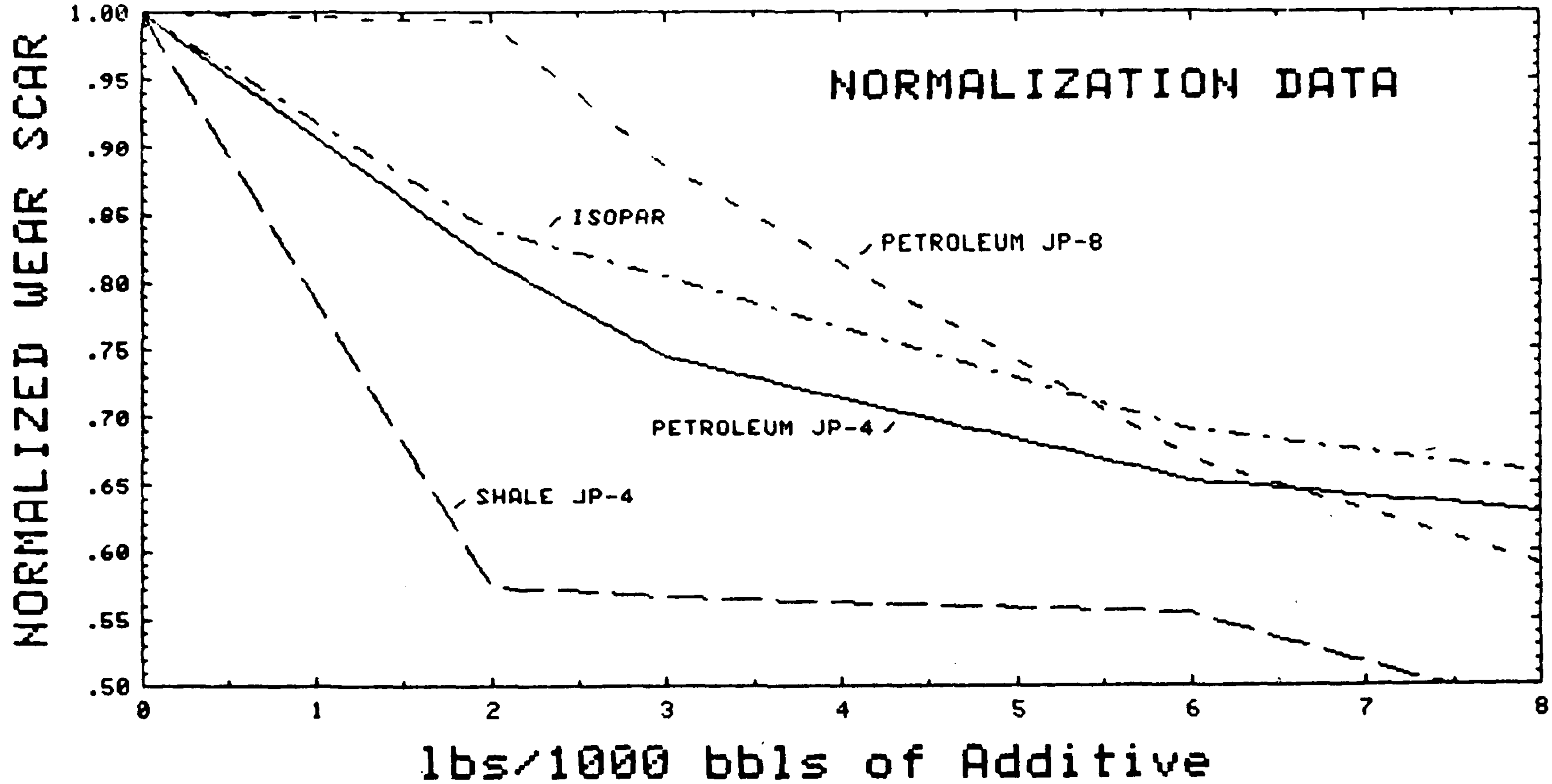

Figure 8b. Normalization Data: C1 at 38 Degrees C

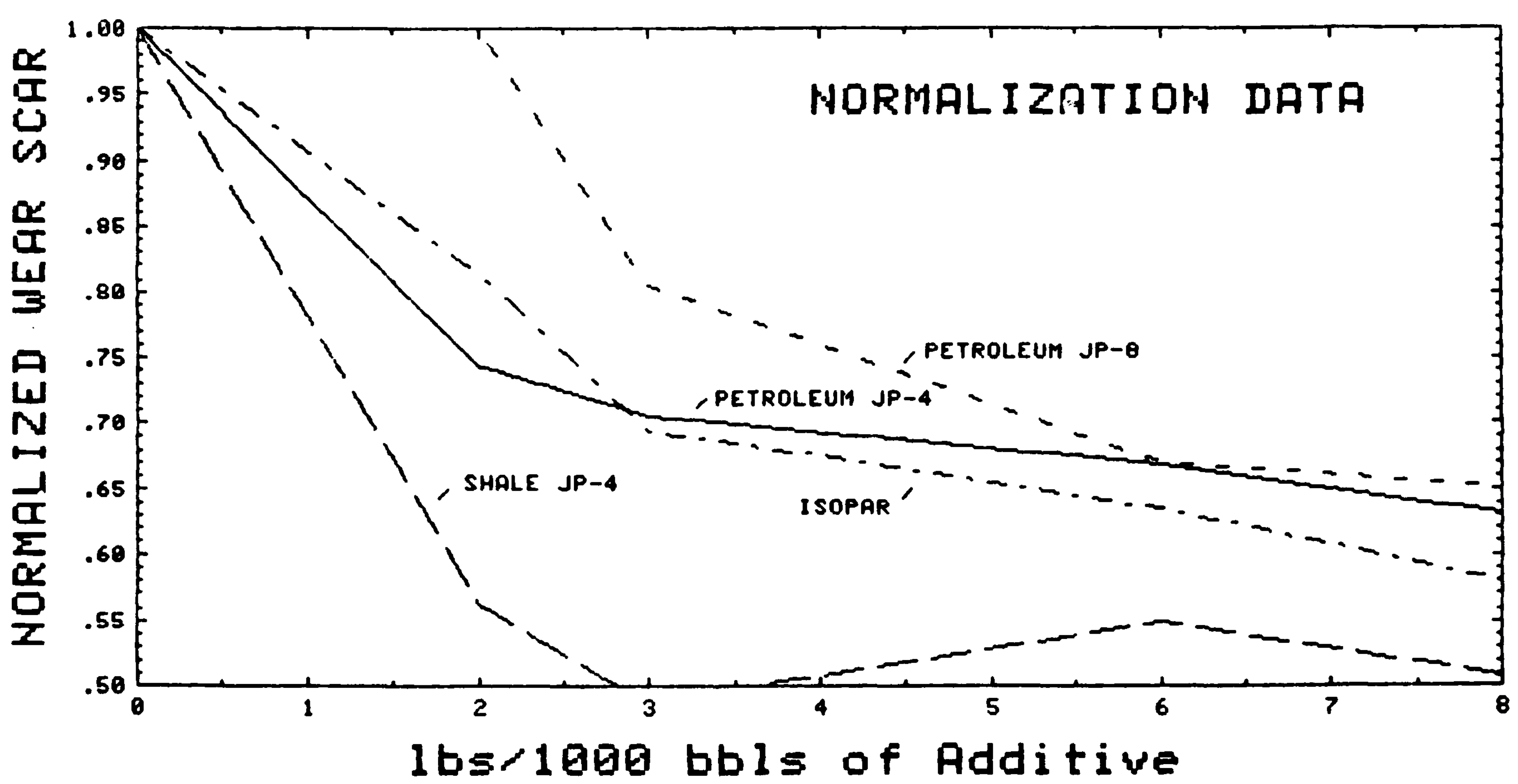

Figure 9a. Normalization Data: C2 at 25 Degrees C

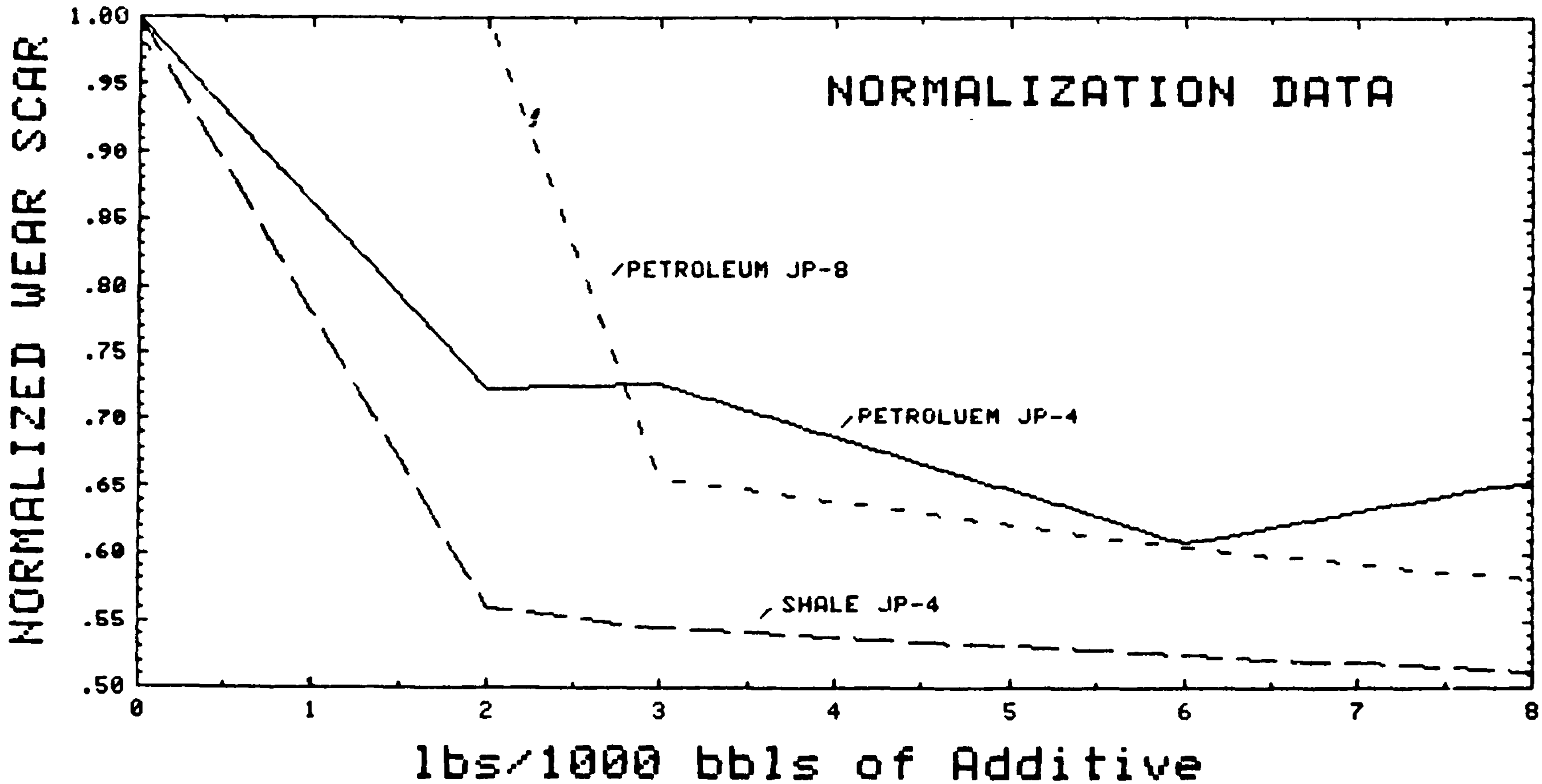

Figure 9b. Normalization Data: C2 at 38 Degrees C

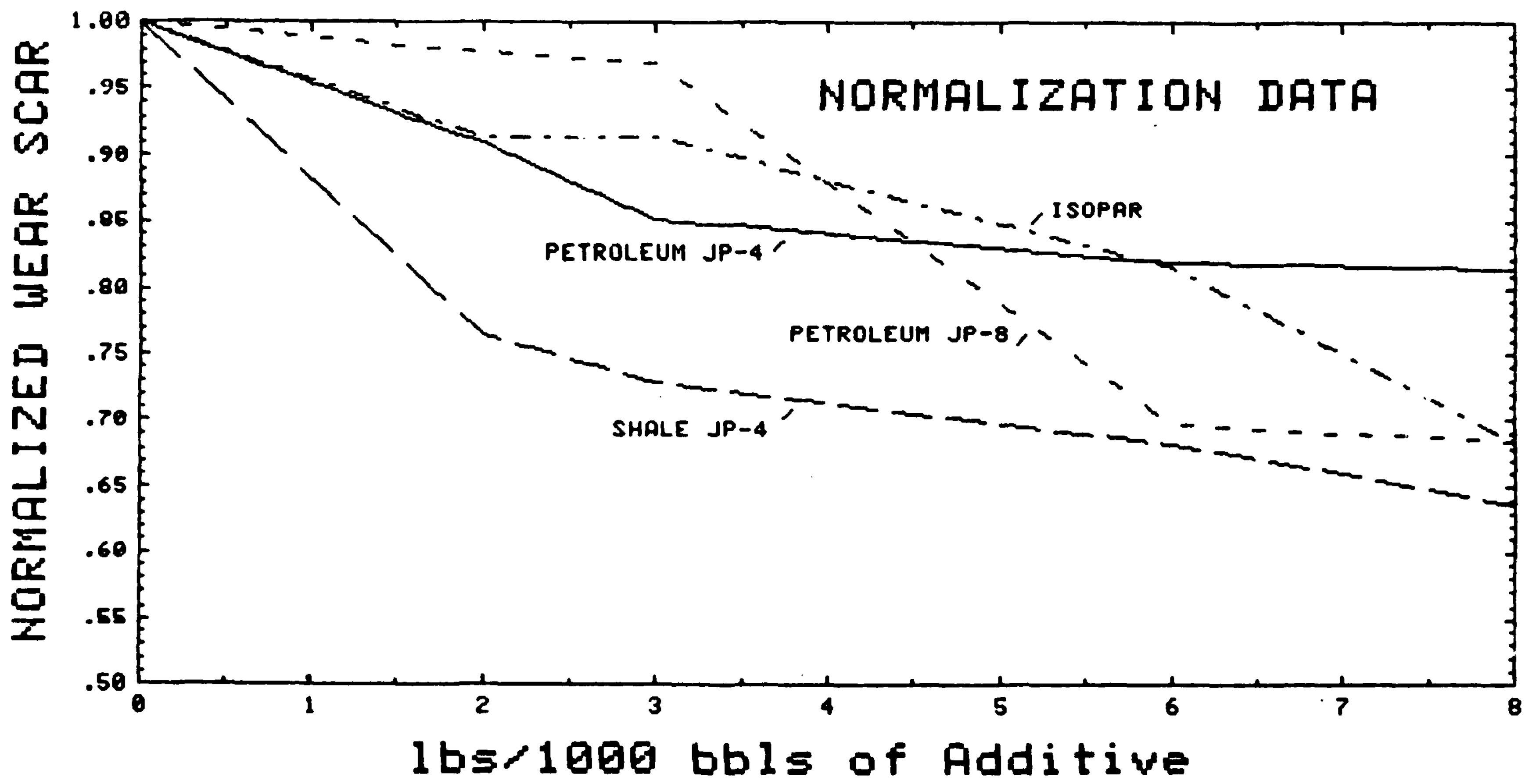

Figure 10a. Normalization Data: C3 at 25 Degrees C

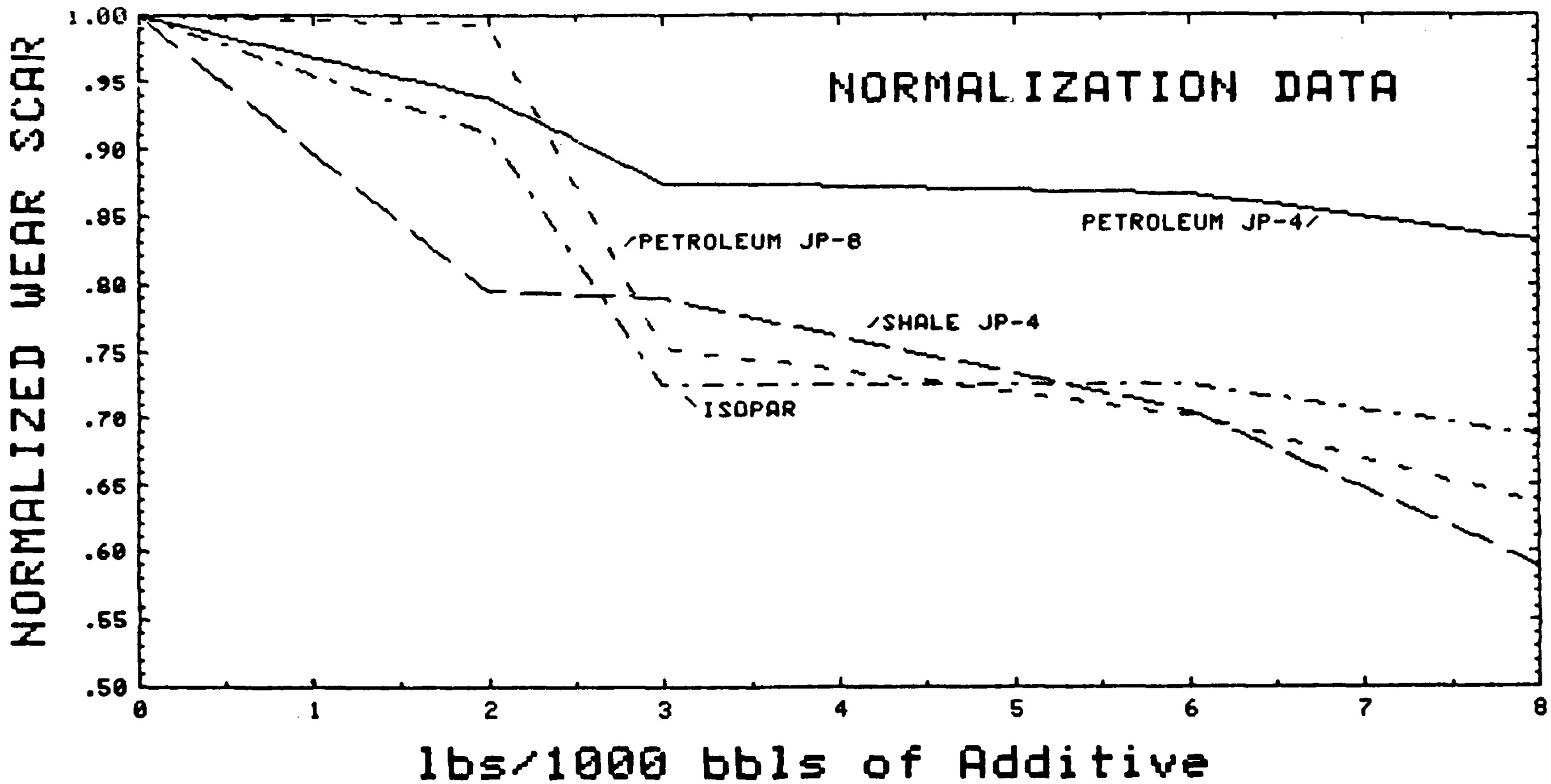

Figure 10b. Normalization Data: C3 at 38 Degrees C

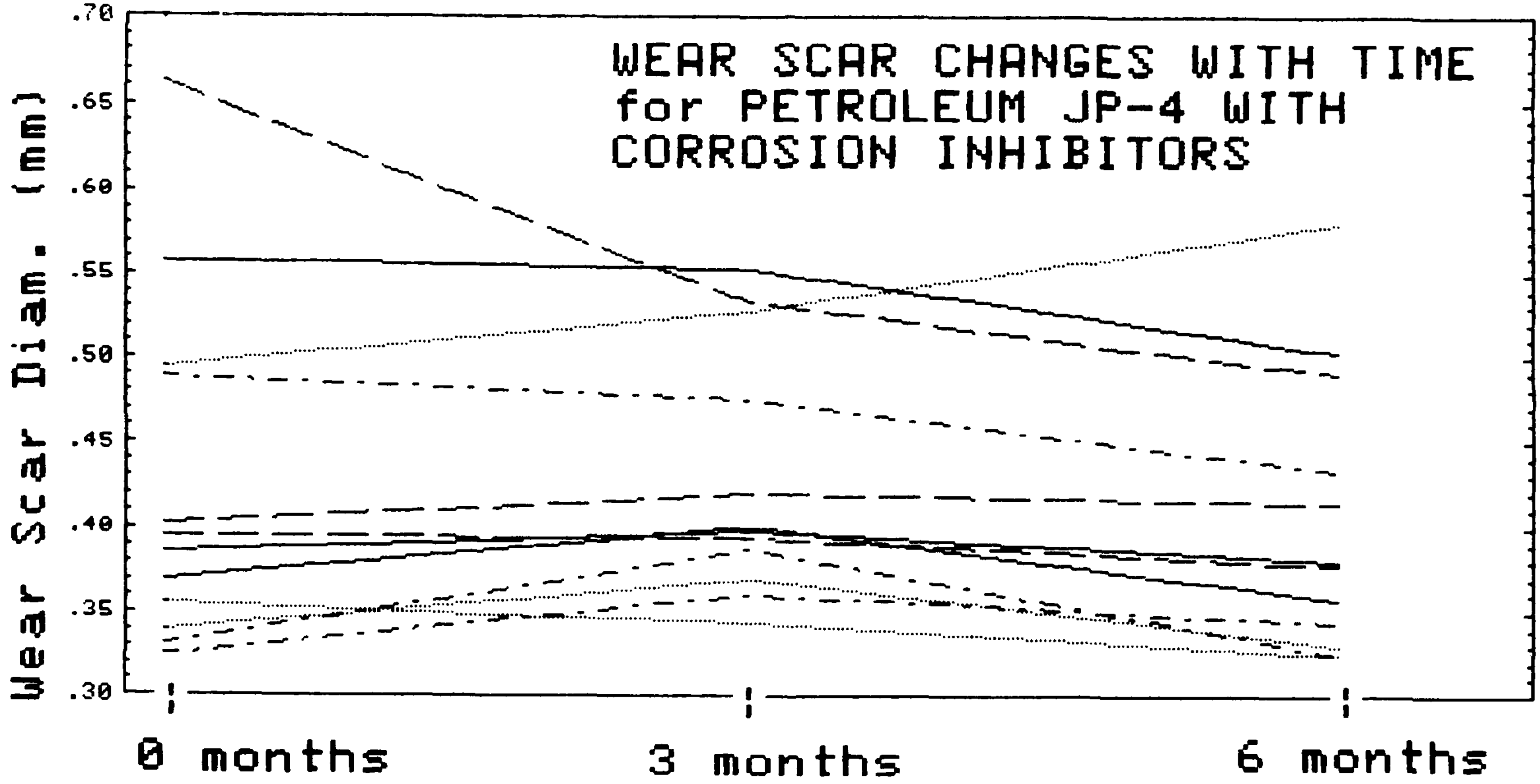

Figure 11. Wear Scar Changes with Time for Petroleum JP-4 with Various Corrosion Inhibitors

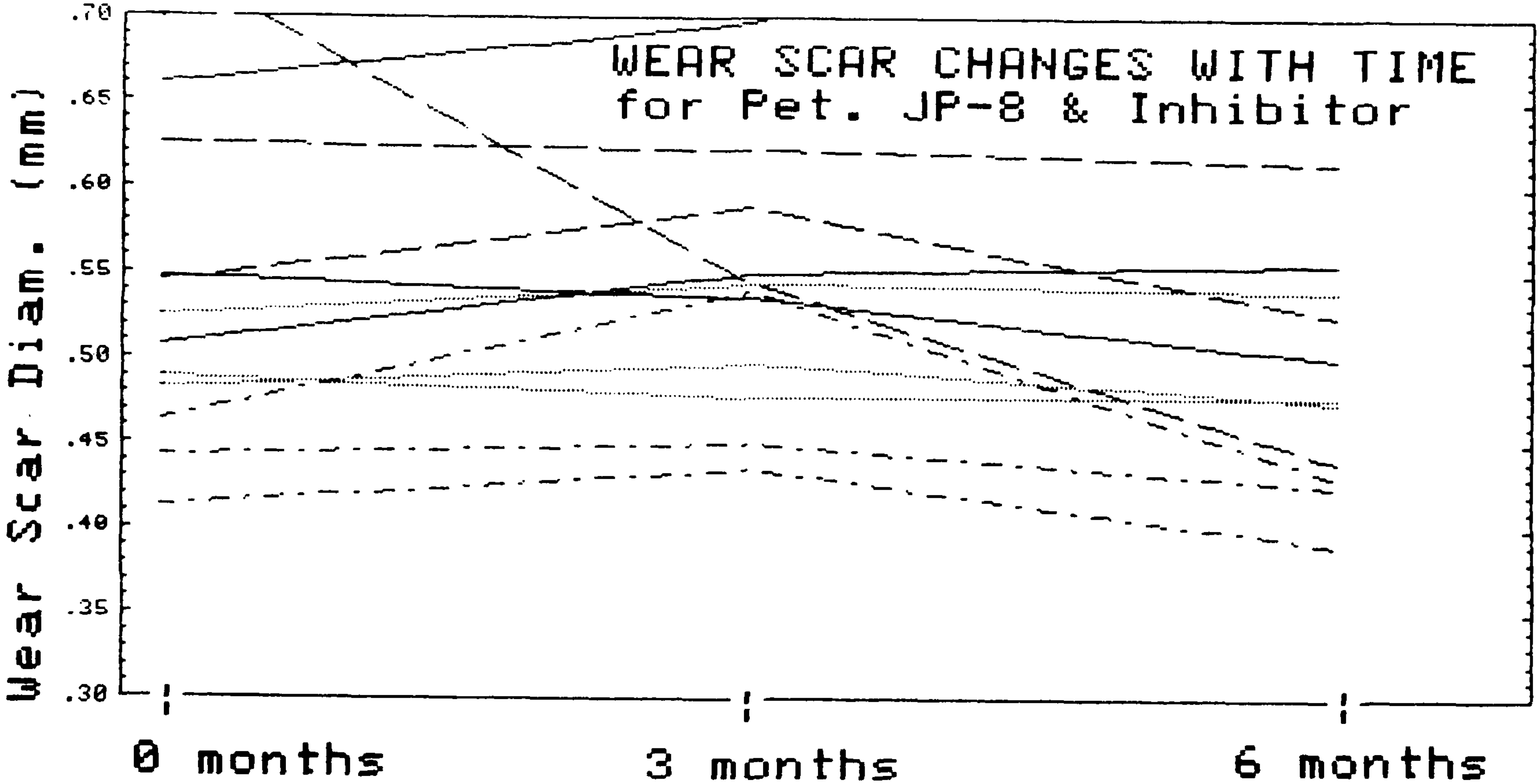

Figure 12. Wear Scar Changes with Time for Petroeum JP-8 with Various Corrosion Inhibitors

three cases out of four) was greater than 0.10 mm.

The changes which came about due to the addition of these additive packages are represented by bar graphs in Figures 13a through 13d and Figures 14a through 14d.

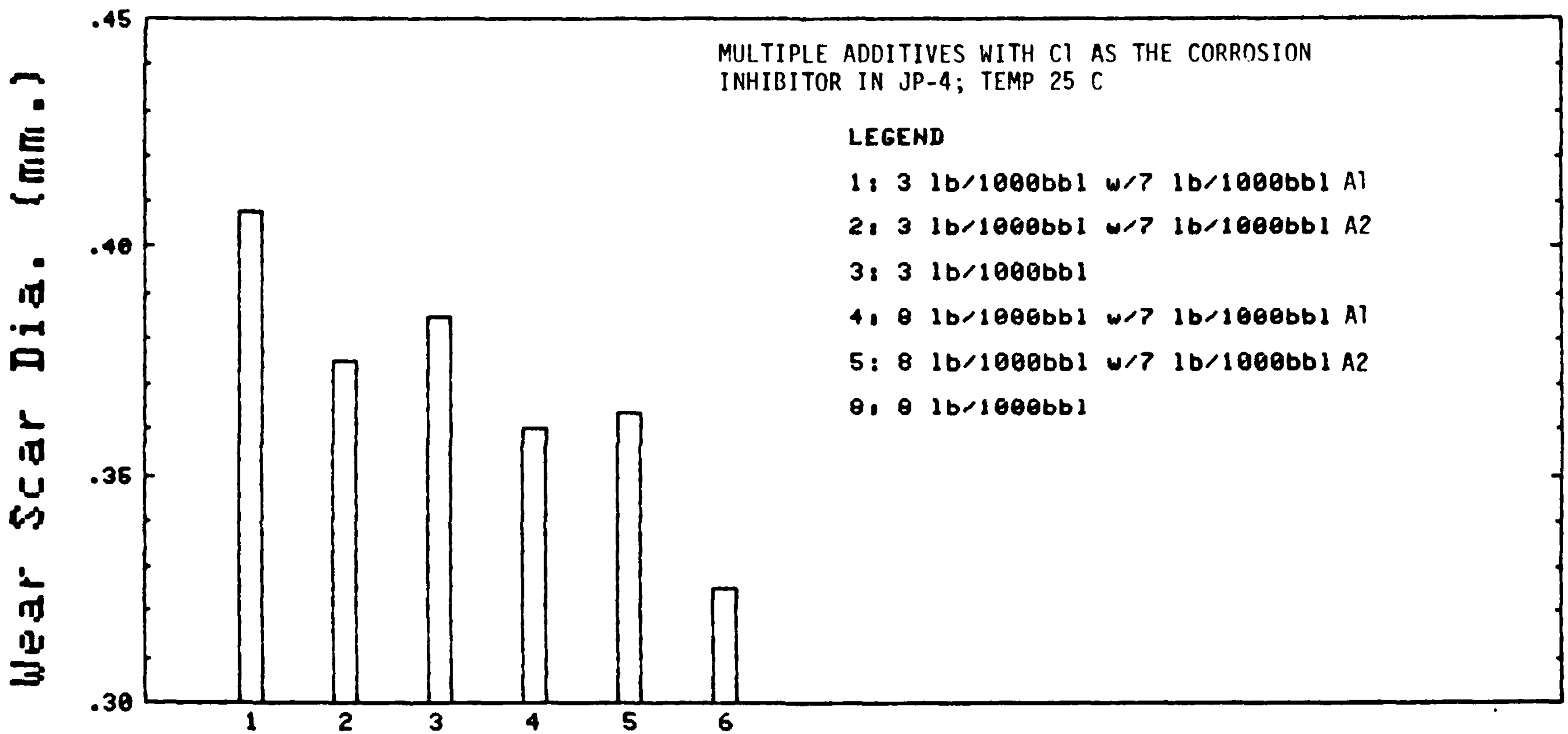

Figure 13a. C1 at 25 degrees C

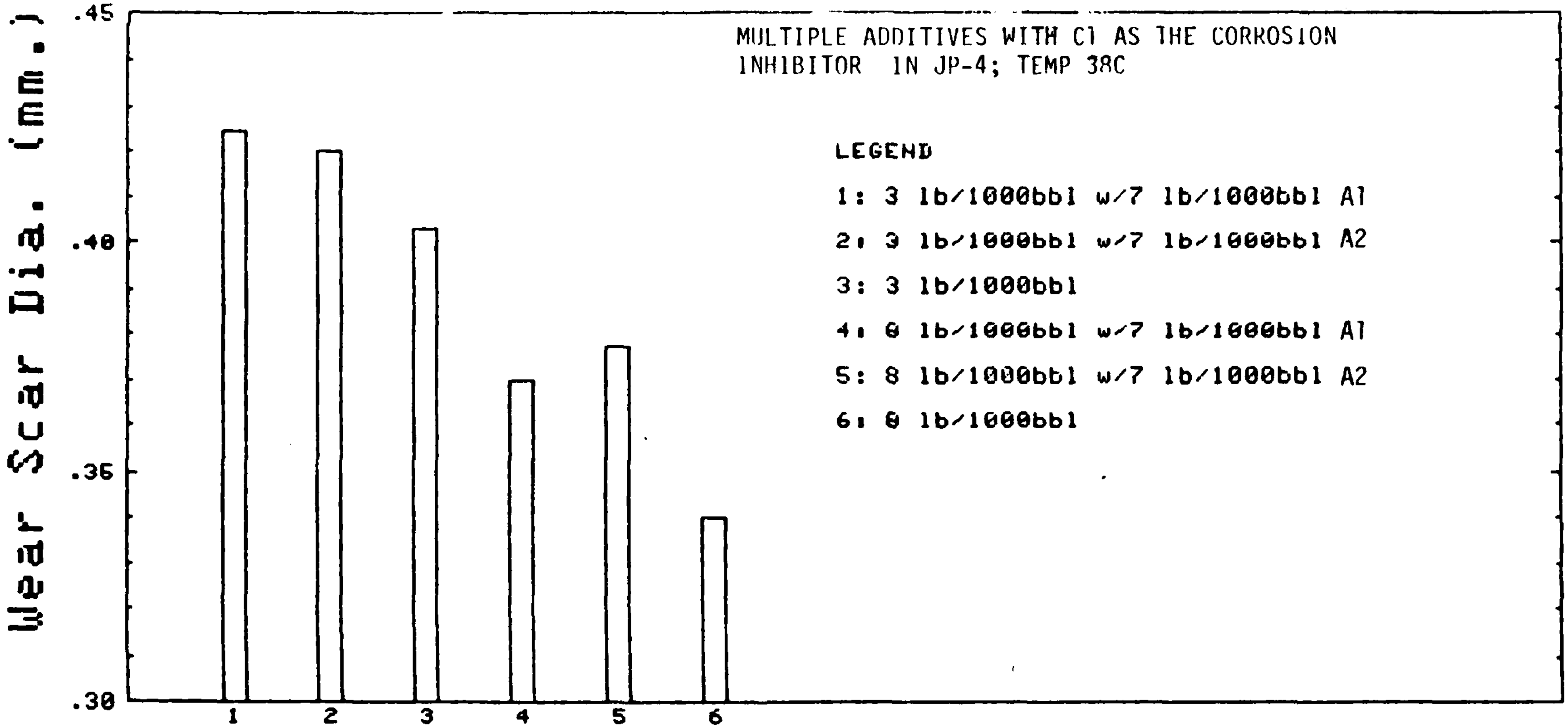

Figure 13b. C1 at 38 degrees C

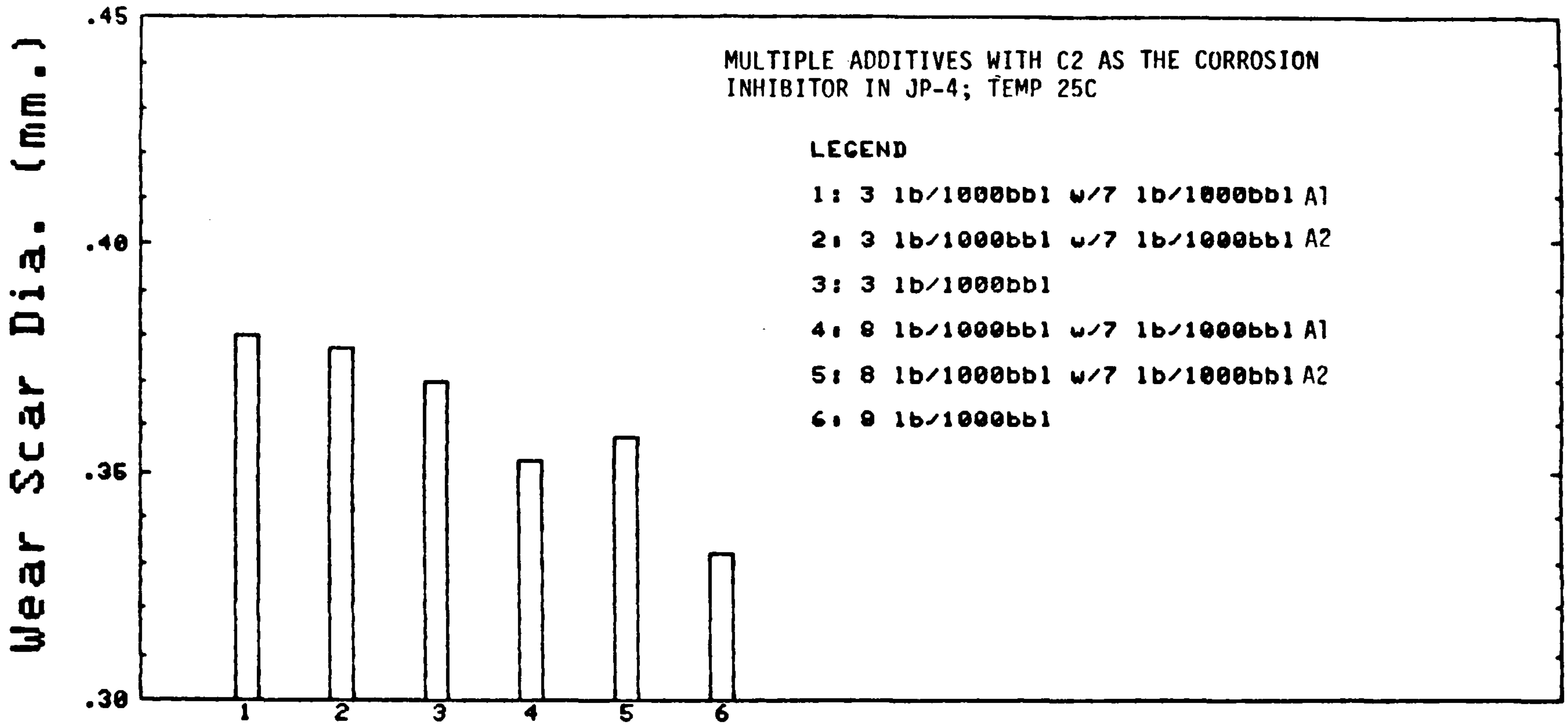

Figure 13c. C2 at 25 degrees C

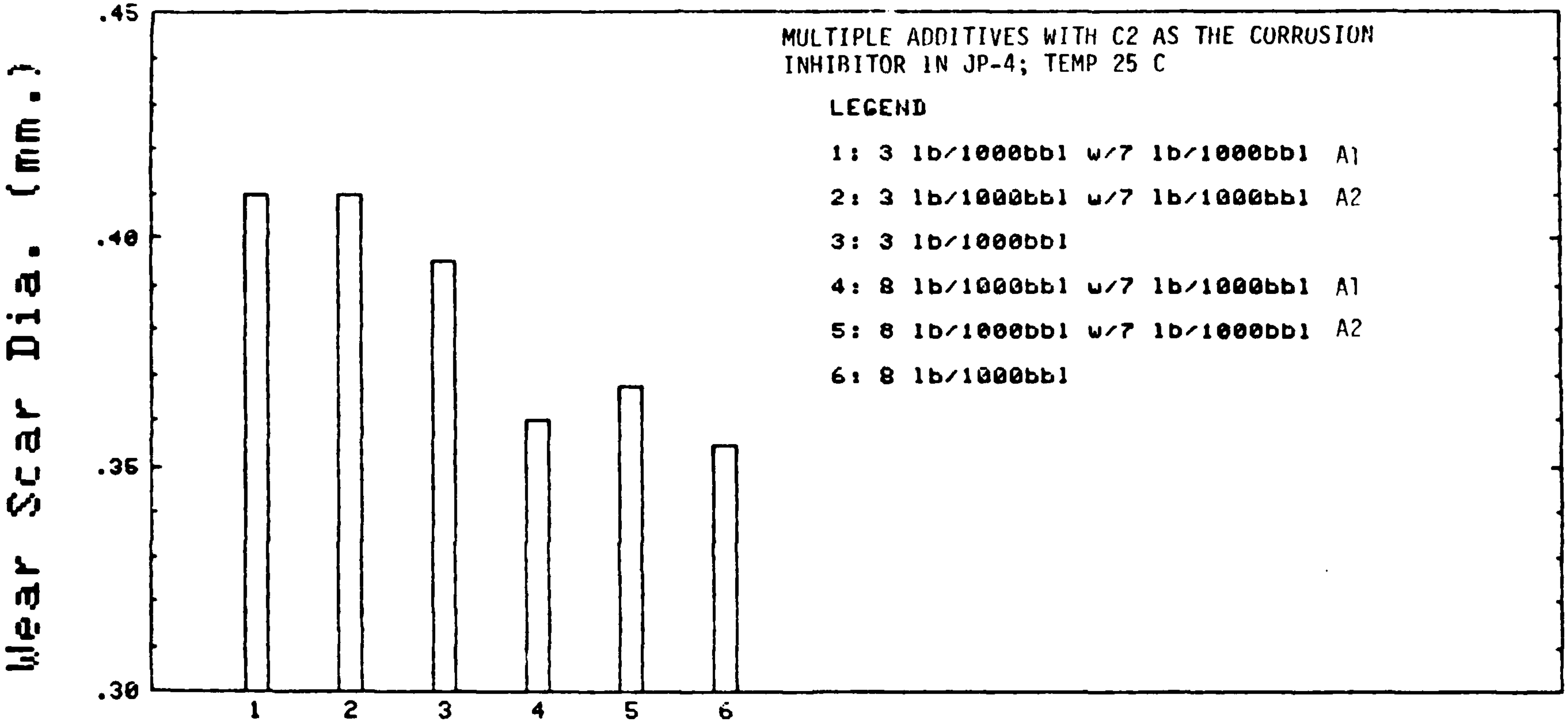

Figure 13d. C2 at 38 degrees C

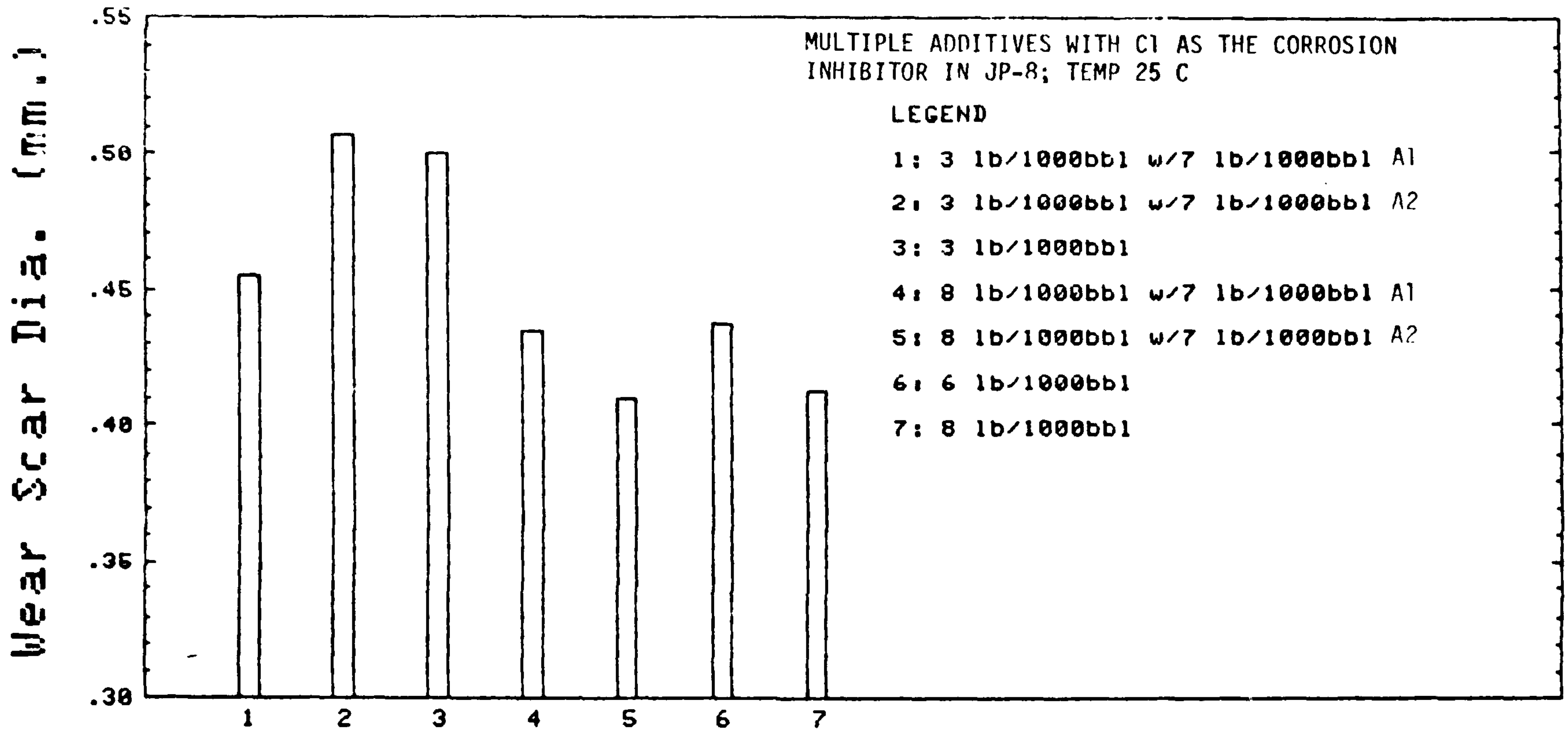

Figure 14a. Cl at 25 degrees C

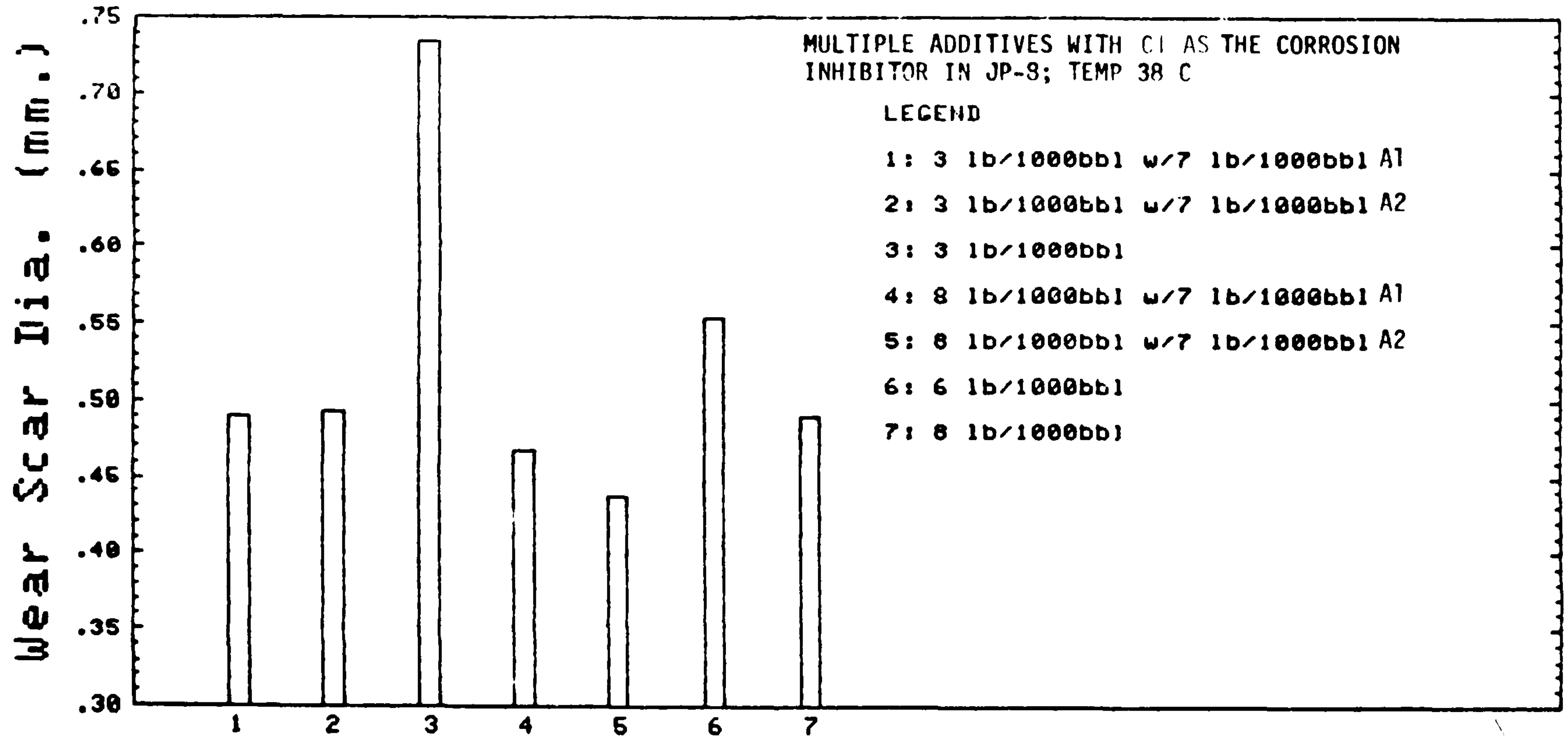

Figure 14b. CI at 38 degrees C

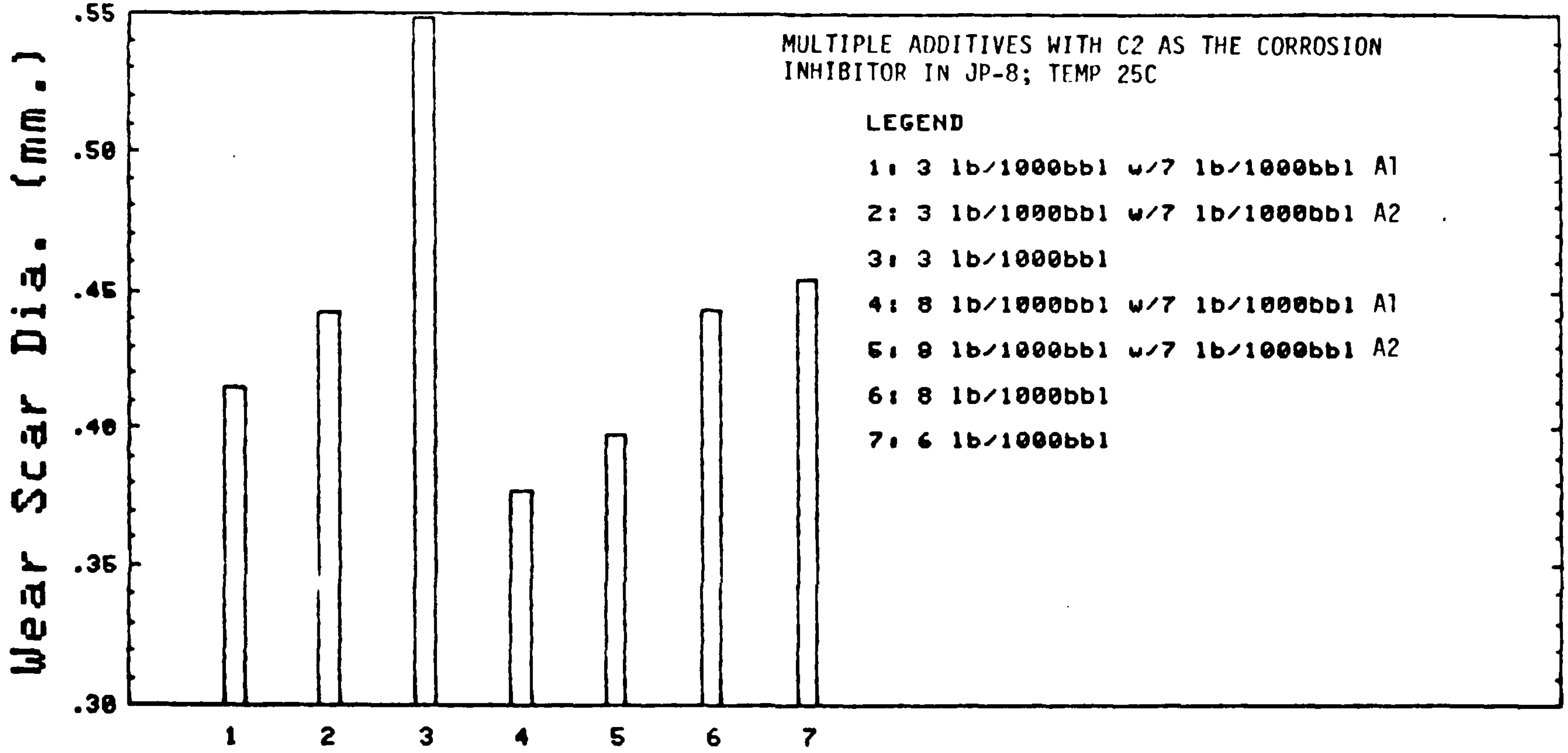

Figure 14c. C2 at 25 degrees C

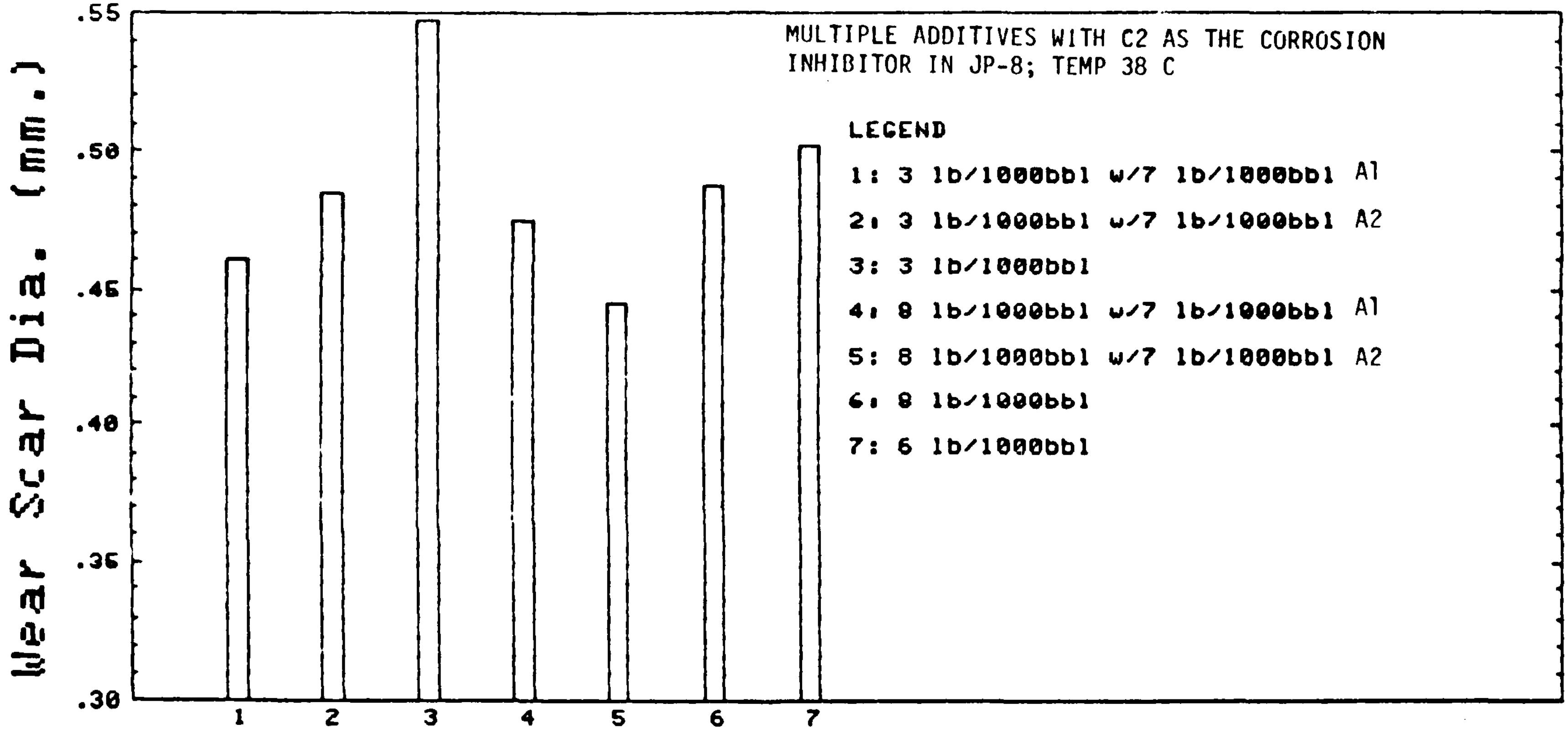

Figure 14d. C2 at 38 degrees C

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A. Effect of Temperature on Wear Scar Diameter

The Interav Ball-on-Cylinder (BOC) tester may be operated at any temperature desired. Higher temperatures were observed, at one time, to produce more consistent results. From this study, it was not evident that the 38 degree C runs were more consistent than the 25 degree C runs. They were, however, different. Figure 15 shows a plot of 38 vs 25 degree runs. Generally, the higher temperature runs produced larger scars than did lower temperature runs. This was not a completely consistent observation throughout all of the data. In short, the data were not found to be any more consistent at one temperature than another - just different. Therefore, the BOC tester should be run at a standard temperature; for simplicity of operation and consistency, 25 degrees C would certainly be acceptable.

B. Advantages of Normalizing Data

As stated earlier, data may be normalized by dividing wear scar diameters by wear scar obtained when running the clay-treated base fuel. This would produce a "normalized wear scar" which would allow one to compare additive effectiveness even with varying concentrations of additives. For example, in Figure 16, it appears that for petroleum JP-4, Corrosion Inhibitor C3 is not the best additive to use for improving lubricity. Corrosion Inhibitor C2 would be a slightly more effective additive (considering all concentrations) than Corrosion Inhibitor C1. Similarly, Corrosion Inhibitor C3 would not be the best lubricity improver in shale fuel (see Figure 17). And for JP-8, Corrosion Inhibitor C1

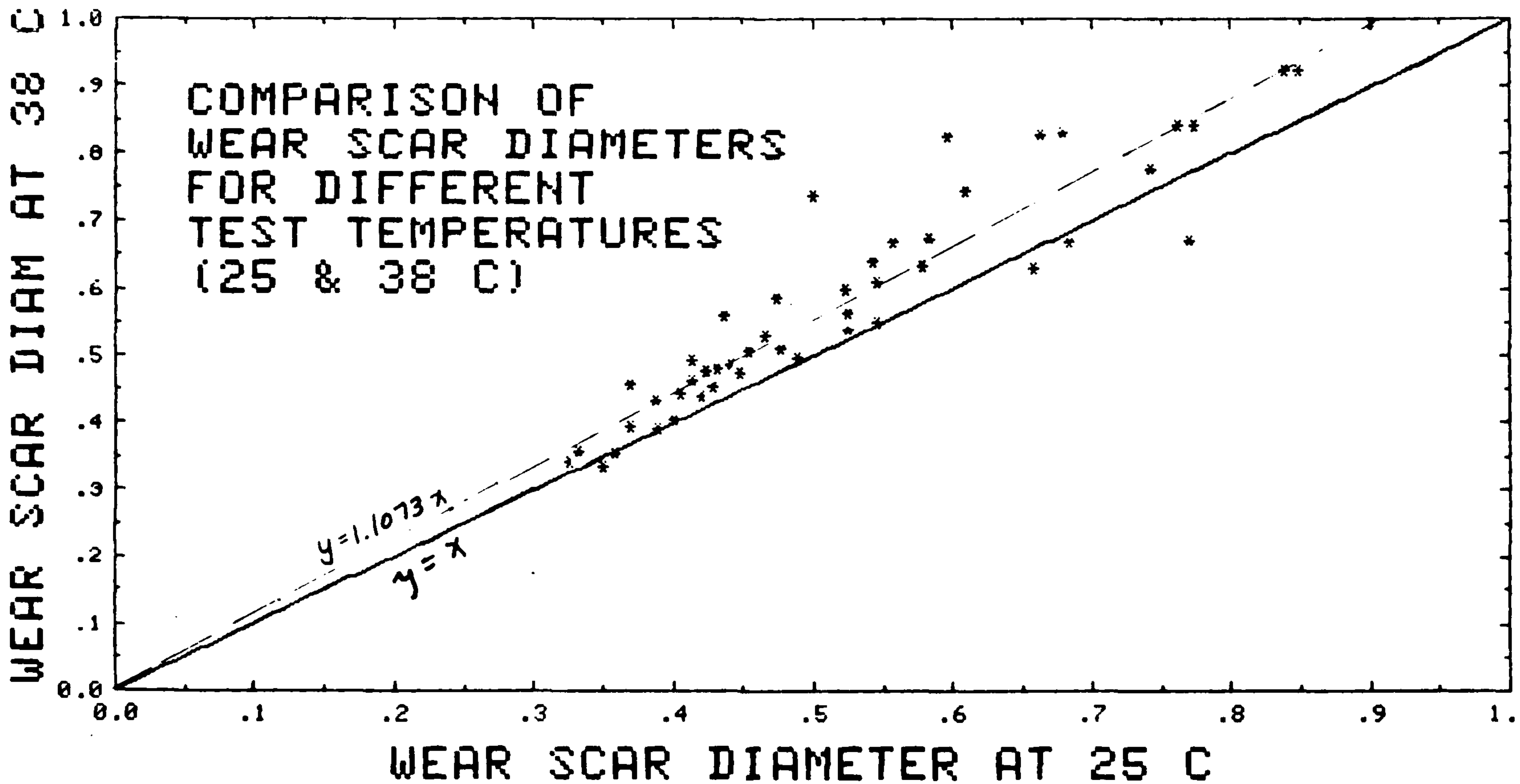

Figure 15. Comparison of Wear Scar Diameters for Two Different Temperatures

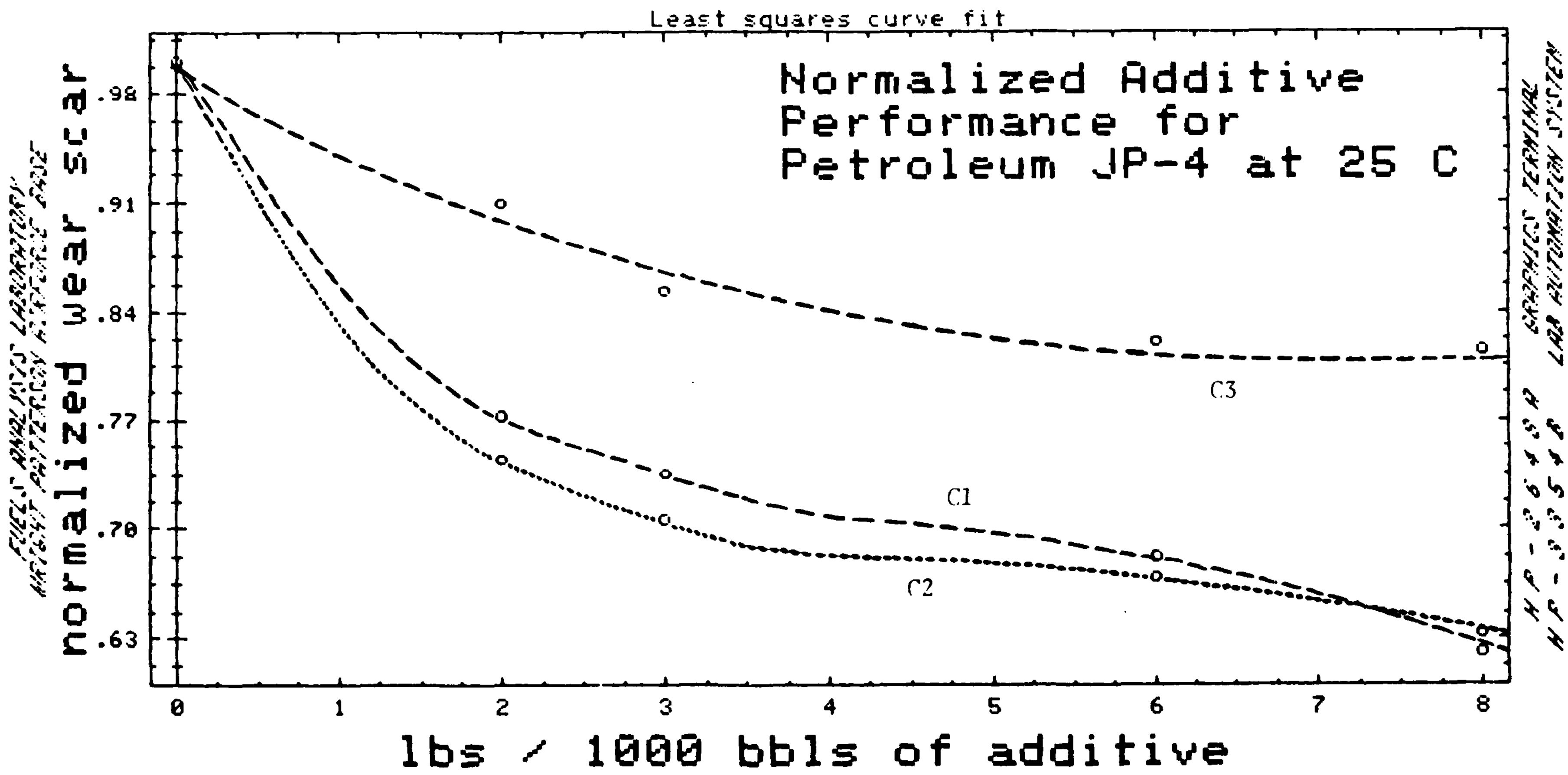

Figure 16. Normalized Additive Performance for Petroleum JP-4

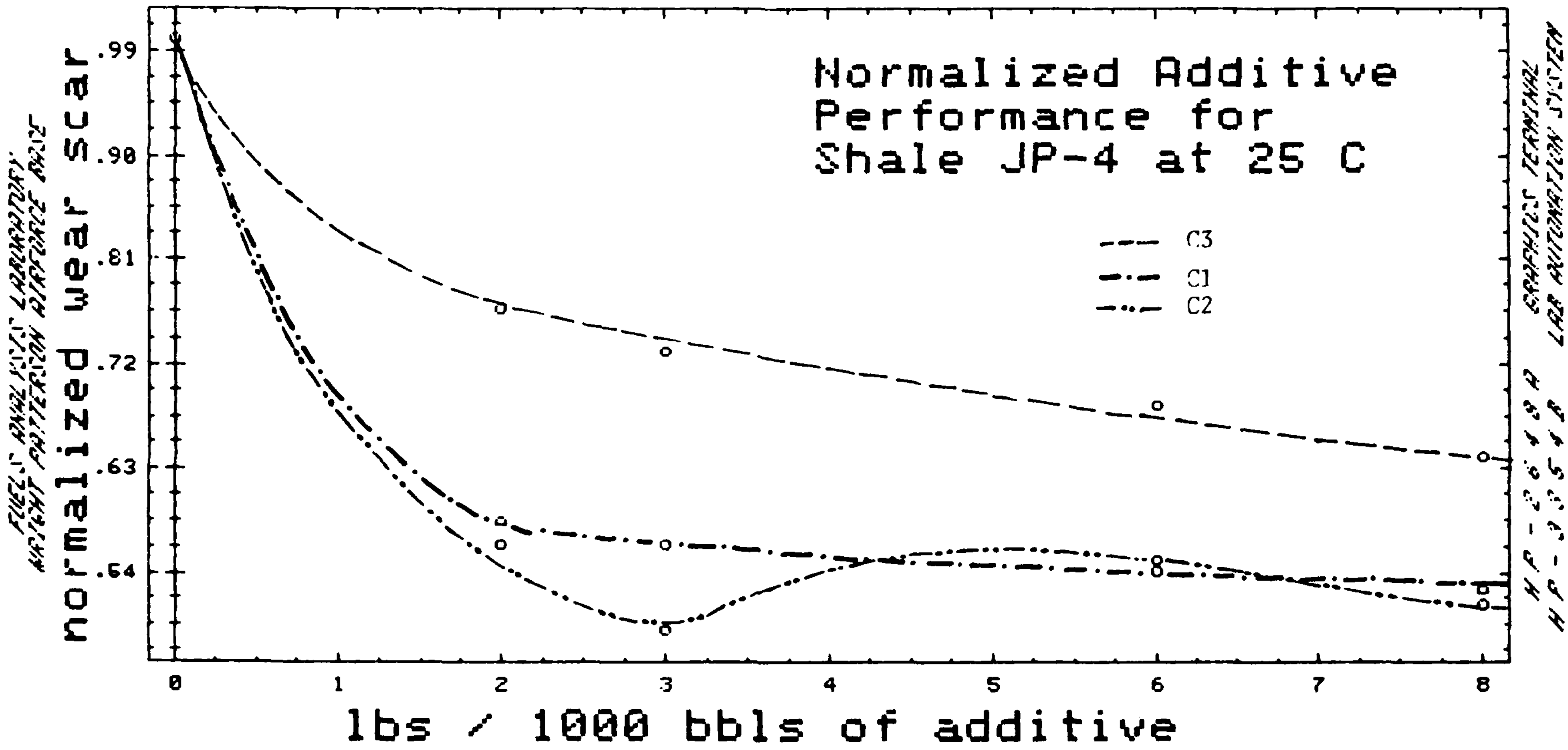

Figure 17. Normalized Additive Performance for Shale JP-4

seems to be the best lubricity improver at all concentrations (see Figure 18). Thus, this normalization procedure provides an easy comparison of the relative effectiveness of lubricity improvers.

C. Determining the "Best" Lubricity Additive

The normalized wear scar procedure may be the best method for the determination of the ideal lubricity additive for a specific fuel. Curves produced may be used to estimate best lubricity characteristics at specific concentrations of additives. For example, Figure 17 shows that Corrosion Inhibitor C2 is a slightly better lubricity improver at minimum effective concentration (3 lbs/1000 bbls) than is Corrosion Inhibitor C1. Yet at other concentrations, lubricity characteristics are almost the same.

As materials and procedures continue to improve, lubricity measurements will begin to become more and more quantitative. Experiments similar to these may have to be carried out in the future with new test equipment and supplies. Until that time, the Interav BOC tester will continue to be an accurate and efficient tool for measuring fuel lubricity.

D. Synergistic Effects

Results of these experiments appeared to indicate that some type of synergism takes effect between corrosion inhibitors and other additives generally found in a fuel. The additive package (antioxidant, icing inhibitor, and anti-static additive) had an effect in the effectiveness of both corrosion inhibitors. Furthermore, the effect varied between fuel types. Wear scar increased when the additive package was added to JP-4 containing corrosion inhibitor while the JP-8 wear scars decreased when the additive package was added. These results were consistent using either Antioxidant A1 or Antioxidant A2. This would suggest that the fuel itself has a very important role in corrosion inhibitor effectiveness. The issue of JP-4 versus JP-8 lubricity should be further investigated, as there appears to be an inherent

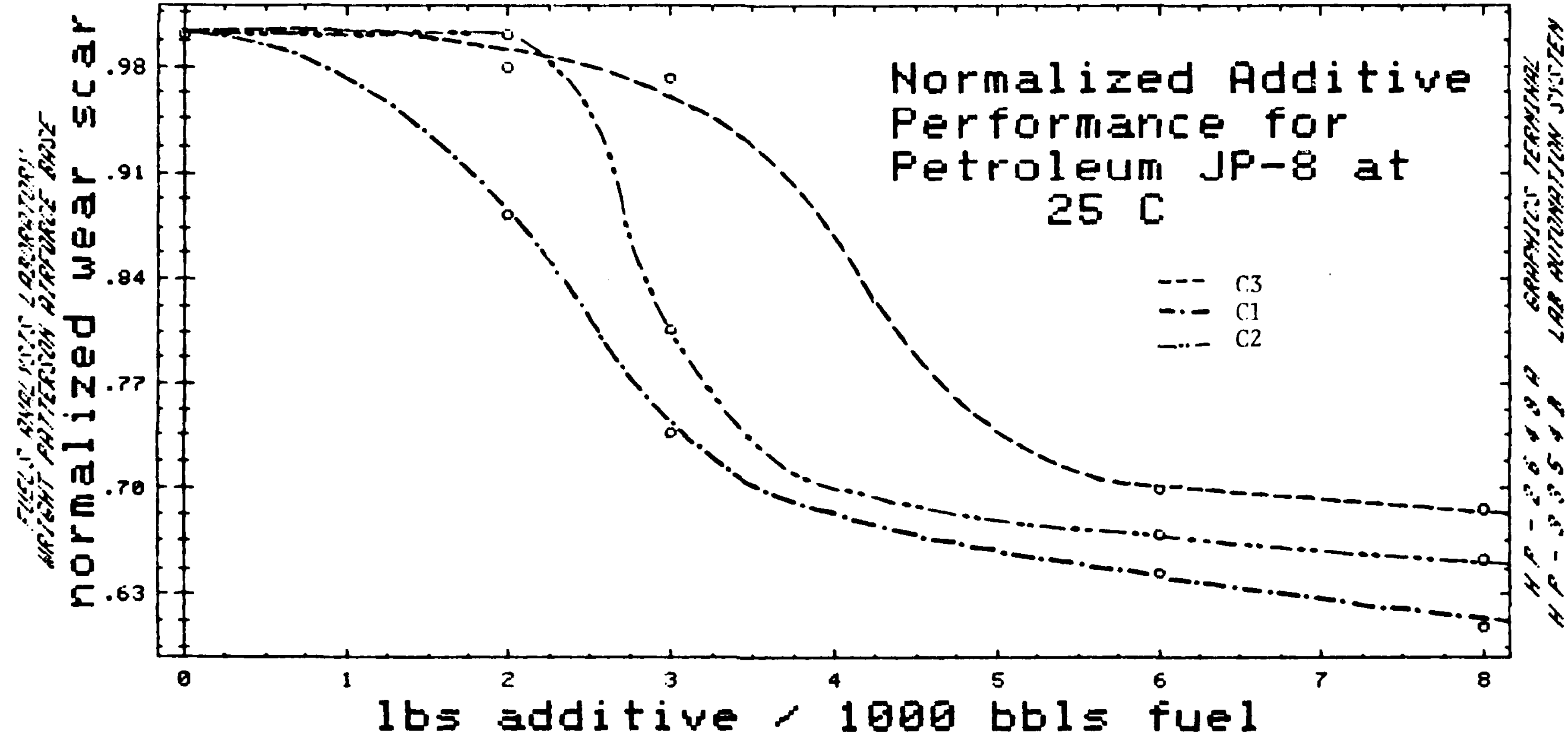

Figure 18. Normalized Additive Performance for Petroleum JP-8

characteristic of each fuel that has a decisive effect on lubricating quality.

E. Storage Effects

From the experiments run in this study, there does not appear to be a significant effect of storage on fuel lubricity. If, however, the fuel is continually being exposed to "fresh" metal surfaces, the inhibitor will undoubtedly plate out and decrease its relative concentration in the fuel. But, for samples stored at ambient temperatures, lubricity will not change significantly over time.

F. Specification Test Results for Base Fuels

Lubricity, for the most part, has always been considered a property which is greatly affected by the minor components of a fuel. Eventually, an experimentor may develop a method of correlating other properties to lubricity in order to determine what truly causes a fuel to have a certain lubricity level. Thus, the specification test results for the fuel used in this study are included in Appendix A. In addition, information for the "Isopar" solvent is given in Appendix B. This additional information may be useful in determining what causes fuel lubricity.

REFERENCES

1. Coordinating Research Council, Inc., Handbook of Aviation Fuel Properties, CRC Report No. 530, 1983.

2. J.K. Appeldoorn, F.F. Tao, Lubricity Properties of High Temperature Jet Fuels, Esso Research and Engineering Company, Air Force Technical Report - AFAPL-TR-66-89, Part II, September 1967.

3. R.K. Johnston, et al, Research on Hydrocarbon Fuels and Related Applications, Southwest Research Institute, Air Force Technical Report - AFAPL-TR-70-5, Part II, May 1971.

4. J. Petrarca, Jr., Aviation Turbine Fuel Lubricity Evaluation of Corrosion Inhibitors, Fuels Branch, Fuels and Lubrication Division, Wright-Patterson AFB, In-house Technical Report - AFAPL-TR-75-47, September 1975.

5. Qualified Products List for Fuel Soluble Corrosion Inhibitors, QPL-25017-13, Amendment 4, 6 May 1982.

6. B.P. Botteri, Decision Recommendation Board (DRB) Report - Transition of Shale JP-4 to the Operational Validation Phase, Fuels Branch, Fuels and Lubrication Division, Wright-Patterson AFB, Final Report, AFWAL-TR-84-2050, May 1984.

7. C. Delaney, "Air Force Aviation Fuel Technology Program, Mobility Fuels Technology Reviews, 25 July 1984.

8. R.C. Striebich, T.L. Dues, Fuel Analysis Report published in Accelerated Mission Test Using Shale Oil Derived JP-4, Part I - TF30 Aviation Gas Turbine Engine, (Westin, J.L.) pages 51-56, Air Force Technical Report, AFWAL-TR-84-2092, Part I, September 1984.

9. J. Petrarca, Jr., Lubricity of Jet A-1 and JP-4 Fuels, Fuels Branch, Fuels and Lubrication Division, Wright-Patterson AFB, In-house Technical Report AFAPL-TR-74-15, June 1974.

10. Ball-on-Cylinder Blueprints, Sketches, Pictures from Interav Inc.

11. Ball-on-Cylinder Operating Manual, Interav Inc. in association with the Fuels Branch, Wright-Patterson Air Force Base, 1984.

12. G.M. Proc, et al, Lubricity of Well Characterized Jet and Broad-Cut Fuels by Ball-on-Cylinder Machine, NASA Technical Memorandum 83807, Lewis Research Center, Cleveland, Ohio, November 1984.

13. "Clay-Treating Procedure," ASTM D2550 Appendix A4, Annual Book of ASTM Standards, Petroleum Products and Lubricants, Part 24, 1980.

14. B. Jauch, et al, U.S. Air Force Technical Survey: JP-4 Jet Fuel Sources and Additives, 1985.

APPENDIX A

SPECIFICATION PROPERTIES OF TEST FUELS

METHOD	SPECIFICATION TEST	PETROL. JP-4	SHALE JP-4	PETROL. JP-8
******	******************************	*********	*********	*********
D156	SAYBOLT COLOR	30	30	25
D3242	ACID NUMBER, mgKOH/g	0.002	0.006	0.002
HPLC	AROMATICS, VOL%	11.9	9.1	16.8
HPLC	OLEFINS, VOL%	0.7	0.4	0.7
D3227	MERCAPTAN SULFUR, WT%	0.000	0.000	0.000
D2622	TOTAL SULFUR, WT%	0.03	0.000	0.0
D2887	DISTILLATION TEMP., DEG. C.			
	INITIAL BOILING POINT	66	28	113
	10% RECOVERED	100	73	156
	20% RECOVERED	116	99	169
	50% RECOVERED	155	155	195
	90% RECOVERED	214	223	235
	FINAL BOILING POINT	265	272	288
D1298	DENSITY, kg/L @15 C	0.771	0.765	0.795
	FLASH POINT DEG. C	--	--	48.0
D2386	FREEZING POINT, DEG C	BELOW -73	-60.5	-69
D445	VISCOSITY @ -20 C cst	--	1.780	4.0
	NET HEAT OF COMBUSTION, MJ/kg	43.5	43.7	18516
D3343	HYDROGEN CONTENT, WT%	14.3	14.8	13.9
D1322	SMOKE POINT, mm	27	27	23.0
	COPPER STRIP CORROSION	1A	1A	1A
	THERMAL STABILITY :			
D3241	DELTA P, mmHg, MAX	0	0	0
	PREHEATER DEPOSIT CODE:	1	1	1
	delta TDR value	1	--	1
D381	EXISTENT GUM, mg/100 mL	0.2	0.4	0.8
D2276	PARTICULATE MATTER, mg/L	--	0.25	0.4
	FILTRATION TIME, minutes	--	5.0	5.0
	WATER REACTION :			
D1094	INTERFACE RATING, MAX	--	--	--
D2550	WSIM, MIN.	--	--	74
	FSII CONTENT, vol%	0.00	0.00	0.00
D2624	ELECTRICAL CONDUCTIVITY, pS/m	0.00	0.00	0.00

Typical Properties

The values shown here are representative of current production. Some are controlled by manufacturing specifications, while others are not. All of them may vary within modest ranges.

Solvency		Test Method		
Aniline point, °C (°F)	88 (190)	ASTM D 611		
Solubility parameter	7.3	Calculated		
Kauri-butanol value	27	ASTM D 1133		
Volatility				
Flash point, PM, °C (°F)	77 (170)	ASTM D 93		
Fire point, COC, °C (°F)	93 (200)	ASTM D 92		
Auto-ignition temperature, °C (°F)	338 (640)	ASTM D 286		
Flammability limits in air, vol % at 21°C (70°F)	0.6-6.5	Calculated		
Distillation, °C (°F)		ASTM D 86		
IBP	207 (405)		JP-4	JP-5
5%	212 (413)		140	340
10%	213 (415)			
50%	223 (434)			
90%	241 (466)			
95%	247 (476)			
Dry Point	254 (490)			
FBP	260 (500)		500	500
Vapor pressure, kPa @ 38°C	4.1	ASTM D 2551		
Vapor pressure, psia @ 100°F	0.6			
Composition				
Hydrocarbon type, mass %		Mass spectrometer		
Total saturates	99.5			
Aromatics	0.4	UV Analysis		
Trace compounds				
Sulfur				
Doctor test	pass	ASTM D 484		
Total sulfur, ppm	1	Microcoulometer		
Peroxides, ppm	<1	Exxon Method		
General Properties				
Average molecular weight	19?	Cryographic		
Bromine index[1]	230	ASTM D 2710		
Copper corr., ½ hr at BP	2	ASTM D 130		
Unsulfonated residue, vol %	99+	ASTM D 483		
UV absorbance		FDA Method		
260-319 mμ	<1.5	21 CFR 172 882		

General Properties, (cont.)		Test Method
320-329 mμ	<0.08	
330-350 mμ	<0.05	
Color, Saybolt	+30	ASTM D 156
Color stability, 16 hr at 100°C (212°F)	+30	
Gravity, °API	49.0	ASTM D 287
Specific gravity @ 15.6°/15.6°C	0.784	Calculated
kg/m³	784	
lb/gal	6.53	Calculated
Refractive index, 20°C	1.4362	ASTM D 1218
Viscosity		ASTM D 445
cp at 25°C	2.46	
cp at 100°C	0.72	
cSt at 0°C	6.80	
cSt at 25°C	3.35	
Odor, bulk	very slight	Exxon Method
Odor, residual	none	Exxon Method
Odor stability	excellent	Exxon Method
Freezing point, °C (°F)	<-60 (<-76)	
Specific heat, liquid, kJ/kg/°C (Btu/lb/°F)		
at 16°C (60°F)	2.05 (0.49)	Calculated from
at 66°C (150°F)	2.26 (0.54)	enthalpy data
at 93°C (200°F)	2.39 (0.57)	
Heat of vaporization, kJ/kg (Btu/lb)		Est. from Maxwell's "Data Book of Hydrocarbons" and report of API Project 44 (1953)
at 100°C (212°F)	307 (132)	
at BP	244 (105)	
Surface Properties		
Demulsibility	excellent	Exxon Method
Interfacial tension, dynes/cm at 25°C	51.0	ASTM D 971
Surface tension, dynes/cm at 25°C	24.8	duNuoy
Toxicological Data		
Inhalation, TLV[2] ppm	300[3]	
Acute Oral LD_{50} (Rat), g/kg	>10	
Acute Dermal LD_{50} (Rabbit), g/kg	>3.1	

(1) Bromine index = Bromine number × 1000

(2) TLV is a registered trademark of the American Conference of Governmental Industrial Hygienists. It is the threshold limit value or occupational exposure limit — the time weighted average concentration for a normal 8-hour workday, 40-hour workweek, to which nearly all workers may be exposed repeatedly without adverse effect. *Refer to the most recent Material Safety Data Sheet for the latest recommended maximum exposure limit.*

(3) A TLV has not been established for this product. The value shown has been recommended by Exxon Corporation Medical Research based on consideration of available toxicological data. Additional data are being obtained to help define a recommended occupational exposure limit more conclusively.

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